Van Amstelpark 8
2629 JJ Delft
The Netherlands

www.tno.nl

T +31 88 866 30 00

TNO report

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Health effects in EU and UK from cooking on gas

Date	8 December 2022
Author(s)	ir. P. Jacobs ing. W. Kornaat
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Summary

Background
The EU is currently updating the Ecodesign legislation with regard to cooking appliances. It concerns Ecodesign Regulation EC No 66/2014 on domestic ovens, gas stoves and range hoods and the Energy Label Regulation EC No 65/2014 on domestic ovens and range hoods. In parallel, the United Kingdom (UK) government is conducting a review of these same two regulations, as they are still applicable under UK law. These regulatory reviews present an opportunity to include requirements in both the EU and UK law that necessitate domestic appliances will not expose users to harmful levels of indoor air pollution.

Research questions
The main research question to be answered in this study is: *What are the health effects from gas cooking appliance indoor air pollution in the EU and UK?*

Sub research questions are:

- *What are the measured concentrations due to gas cooking appliances of NO_2, NO, CO, formaldehyde, methane and ultra-fine particles?*
- *How many EU and UK households are expected to exceed the WHO and European limit values for these contaminants due to gas cooking appliances?*
- *What are the health costs associated with gas cooking appliances?*
- *How will the energy transition, retrofitting and building of airtight new buildings, affect the concentrations of these pollutants?*
- *What are the preferred measures to prevent exposure to these contaminants?*
- *Which factors should be integrated into a representative field study in Phase II?*

Approach
To answer these questions, this study consists of a literature review and a simulation study to determine the NO_2 exposure for typical EU conditions.

The literature study builds upon references from a number of sources including the WHO global air quality guidelines (AQG) from September 2021 and a US study, *Health effects from gas stove pollution* (RMI, 2020). These two sources were complemented by online searches using periodicals such as Indoor Air and other online reference sources to ensure the relevant EU and UK literature and situation are found and addressed. Additional papers were found by the ‘snowball method’.

The simulation study is carried out with the multizone model COMIS. Conditions and dwellings representative for Southern, Eastern and Western EU countries and the UK have been set up. The input parameters include NO_2 emissions, average duration of gas stove use per day, availability and effectiveness of range hoods, ventilation flow and air tightness/infiltration of NO_2 from outdoor air and deposition of NO_2 on surfaces. These have been derived as much as possible from peer reviewed articles and grey literature such as JRC technical reports about cooking appliances.

To supply additional data and to illustrate possible measures, results from relevant TNO laboratory experiments are summarized and presented in this report.

Results

What are the health effects from gas cooking appliance indoor air pollution in the EU and UK?

With regard to children, WHO stated in 2010 that having a gas stove is associated with a 20% increased risk of lower respiratory illness in children. Subsequent research since then has confirmed this finding but also linked gas combustion to the development of ADHD at young children and with electroencephalograph brain response.

In 2010, WHO reviewed the evidence with regard to NO_2 exposure in the indoor environment and concluded: "*The main health outcomes of interest are respiratory symptoms, bronchoconstriction, increased bronchial reactivity, air way inflammation and decrease in immune defence leading to increased susceptibility to respiratory infection. No other health effects have been consistently associated with exposure to nitrogen dioxide in the indoor environment*". WHO concluded that there are relatively few studies on adults. Further the adult study results were not conclusive about a relation between long term exposure and respiratory illness. With regard to short term exposure, human controlled exposure experimental studies indicate minor changes in pulmonary function in people with asthma exposed to 560 $\mu g/m^3$ nitrogen dioxide for up to 2,5 hour. These findings support the 1 hour guideline of 200 $\mu g/m^3$.

In order to quantify the health effect on children use is made of a meta study from 2013 summarizing the results of 41 studies of which a large part were executed in Europe. Children living in households that cook with gas have a 24% increased likelihood of having asthma diagnosed by a doctor. For the EU, with on the average 32.6% of the households cooking on gas, this means that the population attributable fraction (PAF) of paediatric asthma diagnosed by a doctor due to gas stoves amounts 7.3%. In the UK, where the number of households cooking on gas is higher than the EU average, 11.5% of paediatric asthma cases be avoided when the risk factor cooking on gas is removed.

Children living in households that cook with gas have a 42% increased likelihood of having "current asthma", being defined as having self-reported asthma symptoms occurring within the 12 prior months. For the EU this means that the PAF for current asthma amounts 12% and that over 700,000 EU child current asthma cases are attributable to air pollution from gas hobs and ovens.

- *What are the measured concentrations due to gas cooking appliances of NO_2, NO, CO, formaldehyde, methane and ultra-fine particles?*

Nitrogen dioxide (NO_2)

Lab experiments with cooking on gas four typical Western European meals[1] in a 26 m^3 laboratory under ventilation conditions meeting the Dutch Building Decree all lead to hourly average concentrations above the EU and WHO 1-hour limit value of 200 $\mu g/m^3$. The hourly average concentrations varied between 214 and 478 $\mu g/m^3$ and peak concentrations were 1100 $\mu g/m^3$ NO_2.

In a field study in Birmingham peak levels of 1500 $\mu g/m^3$ have been measured when cooking on gas, which were higher than personal exposure peak levels in traffic during commuting.

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[1] O'Leary et al. 2019: see Appendix B for a description of the meals and the presentation of NO_2 data not previously published.

In field studies mainly passive samplers have been used, these samplers give an average value over measurement periods of typically 1 to 2 weeks. In houses equipped with gas stoves the highest nitrogen dioxide concentration is typically found in the kitchen and the lowest in the bedrooms. A study in Lithuania found that average nitrogen dioxide values in the kitchen are typically 2,5 times higher in kitchens with gas stoves than with electric stoves. More cooking leads to higher concentrations in houses with gas cooking appliances, but not in homes with electrical cooking. Electric stoves don't produce NO_2 - so that homes with electric stoves are having NO_2 from other sources (infiltration from outdoor air, smoking, etc). In one California study NO_2 was 165% higher in the apartments compared to single family houses. This indicates a higher risk from gas cooking in smaller spaces.

Nitrogen monoxide (NO)

The concentration of nitrogen monoxide due to cooking on gas is typically two times higher than of nitrogen dioxide. Nitrogen monoxide (NO) is considered not harmful at the concentrations due to cooking on gas. Therefore there are no limit values formulated for the general public. Limit values used in the occupational safety and health for NO are typically a factor 1000 higher than for NO_2. Ozone can easily convert nitrogen monoxide to nitrogen dioxide. Therefore NO might be of importance in the case ozone generating equipment is present like plasma or ionizing air filters.

Formaldehyde (HCHO) and carbon monoxide (CO)

In a large US field study (n=352 homes) gas appliances were not associated with a higher concentration of formaldehyde.
In the same US field study, the highest 1-h CO concentrations were higher in homes that cooked with gas and increased with amount of gas cooking and not using the kitchen exhaust fan. However, the average values for these situations were much lower than the WHO 1-h Air Quality Guidelines (AQG) of 35 mg/m^3. None of the 353 homes measured found CO concentration levels higher than the 1-h WHO AQG. Nonetheless CO remains a concern because of people dying due to leaks or accidents with unvented gas equipment like geysers.

Methane

Methane is in low concentrations not harmful but it is a strong greenhouse gas. We were unable to find any EU literature on methane leakage around gas stoves. Based on US measurements and assuming a ventilation of 12 dm^3/s the equilibrium concentration during non-cooking periods is about 1,3 mg/m^3 (2 ppm). During cooking this concentration is about 6 mg/m^3 (8 ppm). It is estimated that 0,8 - 1,3 % of the used gas is emitted unburned. Using a 20 year timeframe for methane, annual methane emissions from all gas stoves in US homes have an climate impact comparable to the annual carbon dioxide emissions of 500.000 cars.

Ultra-fine particles (UFP)

Cooking on gas emits more ultra-fine particles then electrical cooking.
However in practice, when frying with oil, this difference is difficult to determine as frying emits very large amounts of particles, especially at higher temperatures. Currently there are no limit values or guideline health values for UFP. Peak concentrations from gas and electric stoves occur at a particle size of about 5 nm. In one lab study when boiling water, the emission rate of particles smaller than 10 nm for a gas stove was about 6×10^{12} particles/min while for the electric stove this

is 1,5 x 10^{12} particles/min. However the emissions may vary widely by burner design and operation conditions. Small particles are also generated when electric rings are turned on without a pan. This might be deposited matter burned off the rig. One researcher reported there was no increase in UFP at all when a pot of water was put on the ring. This might be explained by that the heat of the ring is being conducted to the water so that deposited material on the ring does not burn off. As far as we are aware only in two field studies ultra-fine particles have been measured in homes distinguishing cooking on gas and electric stoves. In a Danish study, measuring particles larger than 10 nm with a NanoTracer, no significant difference in ultra-fine particle exposure was found between cooking on gas and electric. However as stated earlier, emission rates for UFP peak at sizes smaller than 10 nm, this size fraction was not measured here. Further the used measurement equipment may not be reliable in the presence of larger cooking particles as it did not include an aerodynamic pre-separator. In the second study, in the UK, a statistically significant difference has been found for UFP exposure between gas and electrical cooking in those houses away from residential traffic.

– *How many EU and UK households are expected to exceed the WHO and European limit values for these contaminants due to gas cooking appliances?*

The answer to this question was developed based on a review of the literature and the use of an indoor air quality simulation tool for NO_2.
- It was found that of the population of 512 million in the EU27 + UK, about 180 million persons (35%) are indoor exposed to emissions due to cooking on gas.
- Based on our simulation results these 180 million citizens will be exposed to values higher than the yearly WHO limit value of 10 μg/m^3 for NO_2.
- In all simulations for the current situation also the WHO daily NO_2 guideline value of 25 μg/m^3 is exceeded.
- Except for the simulation with a large kitchen equipped with mechanical ventilation, in the other simulations for the current situation when cooking on gas the EU outdoor hourly Limit Value of 200 μg/m^3 NO_2 was exceeded indoors above the permitted 18 hours per year.
- Citizens residing in urban areas with increased NO_2 outdoor concentrations and cooking on gas might even be exposed indoors to values exceeding the EU yearly averaged outdoor value of 40 μg/m^3.

It should be noted here however that the simulations for the current situation are based on average cooking behaviour and average building and ventilation conditions and no use of exhaust hoods venting to the outside. Thus people cooking much less on their gas stove, or using an effective exhaust hood venting to the outside may remain below the limit values.

– *What are the health costs associated with gas cooking appliances?*

Cooking on gas has been associated with a number of health issues. Based on 2019 data provided by the International Respiratory Coalition the societal yearly cost of asthma related to gas cooking appliances are estimated at 3.5 billion euro for the EU27 and 1.6 billion euro for the UK. This estimate is based on the monetized Disability-adjusted life years (DALY) and is calculated as the product of the number of DALY and the Gross Domestic Product (GDP) per capita. The total health cost might be larger as this estimate is based on asthma and does not include health effects for which scientific evidence is now emerging.

- *How will the energy transition, retrofitting and building of airtight new buildings, affect the concentrations of these pollutants?*

In airtight buildings there is a slight increase in the weekly averaged NO_2 concentration and number of hours that the concentration is above the EU ambient hourly NO_2 Limit Value of 200 µg/m^3. There are two effects that counteract each other. Due to the higher air tightness there is less infiltration. This leads to less dilution of cooking peaks and thus higher maximum concentrations. On the other side, due to the lower infiltration, less NO_2 from the ambient air enters the houses. Especially in urban regions with a high outside concentration, this can lead to a considerable lower background concentration.

The limited effect of increased air tightness on the indoor NO_2 concentration in the simulation study is in line with the results of an Irish field study in which in 15 dwellings had their indoor air quality measured before and after retrofit. Although the air leakage has been reduced, there was a non-significant decrease of the NO_2 concentration from 6.8 to 6.0 µg/m^3. At the same time after the retrofit there was a significant increase of CO_2 and $PM_{2.5}$.

- *What are the preferred measures to prevent exposure to these contaminants?*

The largest reduction of the NO_2 indoor concentration is reached by switching from cooking on gas to electrical cooking. When switching to electric cooking, the NO_2 and gas flame related ultra-fine particle emissions go to zero. This can be input for requirements in both the EU and UK law that necessitate domestic appliances to prevent exposure of users to harmful levels of indoor air pollution.

Although a range hood is also effective against mitigating $PM_{2.5}$ emissions from cooking oils, field studies towards the effect of range hood with regard to NO_2 are not conclusive. In some studies no or even a detrimental effect on nitrogen dioxide concentration have been reported by a range hood, this may be caused by not using the range hood or that the range hood did not have sufficient capture efficiency, especially for front burner use.

Since cooking with electric burners also produces pollutants like $PM_{2.5}$, kitchen range hoods should be available in all homes and operated as a precaution whenever cooking occurs. Legislation with regard to ventilation provisions should be initiated to make sufficient capture efficiency possible.

- *Which factors should be integrated into a representative field study in Phase II?*

Passive NO_2 measurement
As passive NO_2 sensors are relatively cheap, accurate, small and do not make noise they are the ideal sensors to be placed in kitchen, living room, bedroom and just outside every household to be considered.

Continuous NO_2 measurement
Most field studies up to now have relied on passive sampling which renders weekly or two weekly averaged NO_2 concentrations. For health effects peak concentrations are also important. The WHO and EU therefore have setup hourly guidelines and limit values. In order to verify compliance it is important to measure NO_2 also with continuous measurement, e.g. with a one-minute interval.

Fine particulate ($PM_{2.5}$)
The flue gases due to gas burning do not emit measurable amounts of $PM_{2.5}$. However there are indications that cooking on gas involves higher pan temperatures and therefore might generate more $PM_{2.5}$ due to evaporation of cooking oil Optical $PM_{2.5}$ sensors are relatively small and are often combined with a CO_2 relative humidity and temperature sensor. These sensors are important to describe the measurement conditions. Based on the decay rate of CO_2 when no people are present the air exchange rate can be estimated.

Detailed measurement: ultra-fine particles (UFP)
It is advised to measure in a limited number of houses in the Netherlands and the UK ultra-fine particles. To set up the equipment requires specialist personnel. Peak concentrations of UFP from gas and electric stoves occur at a particle size of about 5 nm. A water based CPC with a detection limit near this size might be the most promising choice for measuring ultra-fine particles in a field study due to the absence of harmful volatile organic emissions. However a water-based CPC might have loss of detection efficiency when being used to measure UFP in the presence of oil droplets from stir frying. Therefore the UFP count reported by such a device in a field study is only representative for meals without (stir) frying. This would involve the need to keep a diary.

Detailed measurement: methane
It is advised to measure in a limited number of houses in the Netherlands and the UK methane leakage due to cooking on gas. As the concentrations are low this requires specialist measurement equipment and personnel. It might even be necessary to temporarily partition the kitchen from the living room with plastic foils.

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Appendices

1 Introduction

The EU is currently updating the Ecodesign legislation with regard to cooking appliances. It concerns Ecodesign Regulation EC No 66/2014 on domestic ovens, gas stoves and range hoods and the Energy Label Regulation EC No 65/2014 on domestic ovens and range hoods. In parallel, the United Kingdom (UK) government is conducting a review of these same two regulations, as they are still applicable under UK law. These regulatory reviews present an opportunity to include requirements in both the EU and UK law that necessitate domestic appliances will not expose users to harmful levels of indoor air pollution. To support these regulatory reviews, evidence concerning the health impacts of gas cooking appliances was compiled in this report.

The overall study of the health impacts of gas cooking appliances consists of two phases. Among other work, the first phase consists of a literature and a simulation study in which air pollution in the home and solutions will be studied. In the second phase, a field-measurement study will be conducted in a number of relevant EU countries to validate the simulation study and to show the current situation with regard to indoor air quality and gas stove usage. This report concerns results and findings for phase 1.

The main research question to be answered in this study is:
What are the health effects from gas cooking appliance indoor air pollution in the EU and UK?

Sub research questions are:
- What are the measured concentrations due to gas cooking appliances of NO, NO_2, CO, formaldehyde and ultra-fine particles?
- How many EU and UK households are expected to exceed the WHO and European limit values for these contaminants due to gas cooking appliances?
- What are the health costs associated with gas cooking appliances?
- How will the energy transition, retrofitting and building of airtight new buildings, affect the concentrations of these pollutants?
- What are the preferred measures to prevent exposure to these contaminants?
- Which factors should be integrated into a representative field study in Phase II?

To answer these questions this study consists of a literature review and a simulation study.

2 Literature review

2.1 Approach

The literature study addresses the key research question and sub-questions, and will build upon the literature database already compiled by Brady Seals at RMI and lead author of the US-report, *Health effects from gas stove pollution*[1]. The WHO *Global air quality guidelines*[2] from September 2021 also constitutes a key report used as a starting point for identifying literature. These two sources are complemented by online searches using periodicals and other online sources to ensure the relevant EU and UK literature and situation are found and addressed. Additional papers are found by the ‘snowball method’. Further keyword searches are conducted combining terms such as “air pollution, indoor”, “gas” or “cooking” with “respiratory tract diseases”, “lung function” or “dementia”. As there has been some concern that susceptibility may vary with age, the epidemiological studies will be presented in two sections – studies in children and studies in adults.

Results from TNO laboratory tests with regard to cooking with gas in combination with recirculation range hoods equipped with carbon or plasma filters are summarized and presented in this study.

2.2 Limit values and standards for cooking air pollutants

The main air pollutants of concern related to gas burning when cooking with gas are nitrogen dioxide, nitrogen monoxide, carbon monoxide, formaldehyde and ultra-fine particles. The following paragraphs explain why nitrogen monoxide and ultra-fine particles do not have limit values and why $PM_{2.5}$ is not taken into account in the literature study in this report.

Nitrogen monoxide (NO) is not considered harmful at the concentrations found when cooking on gas. Therefore there are no limit values formulated for the general public. The concentration of nitrogen monoxide due to cooking on gas is typically two times higher than of nitrogen dioxide[3]. However the limit values used in the occupational safety and health for NO are typically a factor 1000 higher than listed in Table 2 for NO_2. Ozone can easily convert nitrogen monoxide to nitrogen dioxide. Therefore NO might be of importance in the case of indoor environments where ozone generating equipment is present like plasma filters, see paragraph 2.5.

Gas burning in a cookstove or an oven creates ultra-fine particles (UFP). These are particles with a size smaller than 100 nm. The WHO[2] mentions that: “*review studies demonstrated short-term effects of exposure to UFP, including mortality, emergency department visits, hospital admissions, respiratory symptoms, and effects on pulmonary/systemic inflammation, heart rate variability and blood pressure; and long-term effects on mortality (all-cause, cardiovascular, IHD and pulmonary) and several types of morbidity. However, various UFP size ranges and exposure metrics were used, preventing a thorough comparison of results across studies (US EPA, 2019a). Therefore, there was a consensus in the GDG that the body of epidemiological evidence was not yet sufficient to formulate an Air Quality Guideline level.*”

In this literature study $PM_{2.5}$ has not been taken into account as gas burners emit an negligible amount of $PM_{2.5}$. $PM_{2.5}$ is defined as the mass of particles with a diameter smaller than 2.5 µm. O'Leary[4] has measured $PM_{2.5}$ concentrations smaller than 1 µg/m[3] when using the burners in the same way as cooking meal 1 (see Appendix B), but no pans and food were present. Buonanno[5] has measured higher particle number emissions and lower mass emissions for grilling bacon with a gas stove at 171 °C compared to grilling bacon with an electrical stove at 178 °C. The higher particle number can be attributed due to emissions directly coming from the stove. While the higher mass emissions mainly depend on the surface temperature of the bacon, which was higher with the electrical grilling. During cooking $PM_{2.5}$ is mainly formed due evaporation of the oil and the ingredients in the pan. Thus, if the same pan temperature and cooking procedure is used, cooking food with a gas stove or with an electric stove is expected to emit the same amount of $PM_{2.5}$. Similar results have been obtained by Shehab[6] for cooking in houses away from traffic sources. They measured higher UFP concentrations in gas hobs (consistently higher), whilst higher $PM_{2.5}$ concentrations in electric hobs (marginally higher).

Nitrogen dioxide (NO_2)

In 2021 WHO updated its Air Quality Guidelines (AQG)[2] to reflect new scientific evidence on health effects by air pollution. These guidelines are for both outdoor and indoor. The review resulted in a four times lower annual average exposure limit of 10 µg/m^3 compared to the 2005[7] and the 2010[8] version where this annual air exposure limit had been 40 µg/m^3. This is the biggest change made for any of the six pollutants that the AQG cover, see for the other changes in cooking related pollutants Table 1.

The WHO ambient annual average guideline of 40 µg/m^3 was initially based on a meta-analysis of indoor studies[8]: "*It was assumed that having a gas stove was equivalent to an increased average indoor level of 28 µg/m^3 compared to homes with electric stoves, and the meta-analysis showed that an increase in indoor nitrogen dioxide of 28 µg/m^3 was associated with a 20% increased risk of lower respiratory illness in children.* "

The new WHO 2021 standard is based on a meta-analysis of five outdoor NO_2 studies. The average of the five lowest 5 percentile levels in these studies was 8,8 µg/m^3. These data support a long term guideline of no more than 10 µg/m^3 based on the association between long term nitrogen dioxide and all non-accidental mortality[2].

An important note with regard to the application of this guideline to the indoor environment is that Nitrogen Dioxide may act as a proxy for traffic-related air pollution (TRAP)[9]. Nitrogen dioxide measurements are readily available in many countries and the variability of TRAP mixture appears to be well characterised by NO_2.

Table 1 Overview of differences between 2005 and 2021 WHO Air Quality Guidelines (AQGs).

Cooking pollutant	Averaging time	2005 AQG	2021 AQG
NO_2 [µg/m^3]	Annual	40	10
	24 hour	-	25
CO [mg/m^3]	24 hour	-	4
$PM_{2.5}$ [µg/m^3]	Annual	10	5
	24 hour	25	15

Table 2 gives an overview European Limit Values for nitrogen dioxide (NO_2) and compares this with the WHO AQG's.

Table 2 European limits and guidelines for nitrogen dioxide (1 μg/m³ = 0.523 ppb).

	Indoor/ outdoor	**yearly [μg/m³]**	**24 hour [μg/m³]**	**1 hour [μg/m³]**
EU 2008/EC/50[10]	outdoor	40	-	200*
WHO 2021[2]	both	10	25	200

** not to be exceeded more than 18 times a calendar year.*

Carbon monoxide (CO)
Table 3 gives an overview of European Limit Values and the WHO AQG for carbon monoxide (CO).

Table 3 European limits and guidelines for carbon monoxide (1 mg/m³ = 0.858 ppm).

	Indoor/ outdoor	**24 hour [mg/m³]**	**8 hour [mg/m³]**	**1 hour [mg/m³]**	**15-minute [mg/m³]**
EU 2008/EC/50[10]	outdoor	-	10	-	-
WHO 2021[2]	both	4	10	35	100

Formaldehyde (HCHO)
Table 4 lists limit and guideline values for formaldehyde. Formaldehyde is typically an indoor air pollutant, however the EU has not set limit values in its regulation on indoor air quality. Additionally, since Formaldehyde is an indoor pollutant, the EU does not set any Limit values outdoors. WHO[8] has set a 30 minutes interval guideline of 0.1 mg/m³ to prevent sensory irritation. Evaluation of long-term effects, including cancer, yielded values above this short term guideline. In the Netherlands the Building Decree specifies for buildings a maximum legal value of 120 μg/m³, which is in line with the pre-rounded WHO value.

ISIAQ working group 34 has developed a database to share worldwide indoor environmental quality values: http://www.ieqguidelines.org. Most values reported in this database are in line with the WHO 30 minutes guideline. However in some countries lower values are given for longer exposure time intervals.

Table 4 European limits and guidelines for formaldehyde (1 μg/m³ = 0.814 ppb).

	Indoor/ outdoor	**30-minute [μg/m³]**
EU 2008/EC/50[10]	outdoor	-
WHO 2010[8]	indoor	100

2.3 Health effects from gas cooking

In 2010, WHO[8] reviewed the evidence with regard to NO_2 exposure in the indoor environment and concluded: "*The main health outcomes of interest are respiratory symptoms, bronchoconstriction, increased bronchial reactivity, air way inflammation and decrease in immune defence leading to increased susceptibility to respiratory infection. No other health effects have been consistently associated with exposure to nitrogen dioxide in the indoor environment*". Subsequent research since then has confirmed this finding but also linked gas combustion to the development of ADHD at young children[11,12] and with electroencephalograph brain response[13].
As there has been concern that susceptibility may vary with age, the epidemiological studies will be presented in two sections: studies with children and studies with adults.

Children
WHO[8] stated that having a gas stove is associated with a 20% increased risk of lower respiratory illness in children. This is based on a meta-analysis of 11 studies that already has been published by Hasselblad[14] in 1992.
In 2013 a new meta-analysis[15] was carried out, summarizing the results of 41 studies of which a large part were executed in Europe. It suggests that children living in a home with gas cooking have a 42% increased risk of having experienced asthma symptoms in the last 12 months (current asthma), a 24% increased risk of ever being diagnosed with asthma by a doctor (lifetime asthma) and a 32% increased risk of having current and lifetime asthma.

Based on the percentage households cooking on gas p with the following formula the population attributable fraction (PAF) can be estimated[16]:

$$PAF = \frac{p\ x\ (RR-1)}{p\ x\ (RR-1)+1}$$

RR is relative risk (or odds ratio) of asthma for children exposed to cooking on gas. The PAF is here the theoretical proportion of asthma burden that could be averted when the risk factor cooking on gas is removed. By multiplying the PAF with the % children having asthma the number of children having asthma due to cooking on gas can be estimated.

The 2013 meta study[15] lists a relative risk (RR) of 1,24 for lifetime asthma, meaning ever have being diagnosed with asthma by a doctor. The % households cooking on gas p has been derived from Eurostat 2019 data[17]. For the EU, with on the average 32.4% of the households cooking on gas, this means that the population attributable fraction (PAF) of paediatric asthma diagnosed by a doctor due to gas stoves amounts 7.3%. In the UK, where the number of households cooking on gas is higher than the EU average, 11.5% of paediatric asthma cases be avoided when the risk factor cooking on gas is removed.

In Table 5 an estimate is presented for number of children having asthma symptoms occurring within the last 12 months (current asthma) due to cooking on gas. The latest data of asthma prevalence on European scale is from the ISAAC 2003 study[18]. In this study children being 13-14 years old filled in a questionnaire with for "current asthma", being defined as having asthma symptoms occurring within the 12 months prior to the questionnaire. The 2013 meta study[15] lists a relative risk (RR) of 1,42 for current asthma. For the EU and the UK this means that the PAF for current asthma are 12 and 18,5% respectively. The percentages of children up to 14 year within the EU and the UK in 2019 as share of the total population are 15 and 18% respectively[19]. For a number of countries data is missing. These are excluded from the calculation. In total for the EU27 the number of children having asthma symptoms occurring within the last 12 months due to cooking on gas is estimated at more than 700.000. For the UK this number of children is estimated at more than 500.000. The relative high amount of children estimated in the UK having current asthma is caused by the relative high prevalence of children with asthma which is higher than any EU country, the large number of households cooking on gas and the higher share of children within the total population.

Due to less ambient air pollution[20] and improved housing the paediatric asthma incidence might have been lowered since 2003. But the observed changes in several countries where data on trends is available suggest that trends are in both directions (increasing[21] or decreasing[22] asthma rates) depending on the country. Data from the Global Burden of Disease database[23] for EU27 indicate that the asthma prevalence for children up to 14 year in the EU27 is rather constant between 2003 and 2019. In the GBD study it is not entirely clear whether the data are self-reported or diagnosed by a doctor, but the trend is quite clear. Therefore it is concluded that the 2003 ISAAC data can still be used to estimate the EU wide asthma prevalence.

	households cooking on gas	PAF	% children with asthma in 2003	# children	# children with current asthma due to cooking on gas
Italy	68,7%	22,4%	11,4%	9.190.198	234.605
Slovakia	68,5%	22,3%		829.866	-
Netherlands	65,4%	21,5%	13,0%	2.604.501	72.961
Romania	64,9%	21,4%	8,9%	2.924.129	55.744
Hungary	60,4%	20,2%	7,8%	1.468.373	23.176
Czechia	49,2%	17,1%		1.627.765	-
Luxembourg	48,0%	16,8%		95.149	-
Poland	43,7%	15,5%	6,1%	5.752.685	54.419
Lithuania	42,1%	15,0%	2,5%	413.788	1.554
Latvia	39,8%	14,3%	7,2%	286.702	2.956
Spain	33,5%	12,3%	13,9%	7.106.726	121.845
France	31,7%	11,7%	12,6%	9.921.574	146.885
Belgium	26,7%	10,1%	8,5%	1.761.623	15.098
Croatia	22,8%	8,7%	5,2%	624.001	2.836
Ireland	21,1%	8,1%	21,5%	750.543	13.136
Estonia	16,9%	6,6%	4,8%	201.633	641
Portugal	10,0%	4,0%	14,7%	1.549.900	9.183
Slovenia	9,9%	4,0%		315.999	-
Austria	5,4%	2,2%	7,0%	1.368.972	2.125
Germany	2,9%	1,2%	8,0%	12.735.159	12.260
Denmark	2,6%	1,1%		880.415	-
Bulgaria	2,5%	1,0%	5,5%	1.056.164	604
Sweden	1,5%	0,6%	12,0%	1.535.088	1.153
Finland	0,6%	0,3%	7,7%	842.189	163
Greece	0,4%	0,2%	4,5%	1.584.304	120
Cyprus	0,0%	-		183.519	-
Malta	0,0%	-	14,1%	67.115	-
EU27	32,6%	12,0%		67.678.078	771.464
UK	53,9%	18,5%	25,1%	12.028.800	557.326

Table 5 Estimated number of children with current asthma (having self-reported asthma symptoms occurring within the last 12 months) due to cooking on gas based on 2003 asthma prevalence data (sources: Eurostat 2020[19], Eurostat 2022[17] European Respiratory Society 2003[18]).

From the 2013 meta-study[15] concluded further that per 15 ppb (29 µg/m^3) increase in indoor nitrogen dioxide, children have a 15% increased risk of having current wheeze. The meta-analysis found no increase in the risk of asthma in relation to the indoor exposure to nitrogen dioxide and no increase of wheeze in relation to the presence of a gas cooking device. The finding of an association between gas cooking and asthma in the absence of an association between measured NO_2 and asthma suggest that gas cooking may act as a surrogate of other pollutants produced by gas cooking than NO_2 alone[15]. This is supported by an Australian[24] study, where the association between gas cooking and respiratory symptoms remained significant after adjustment for the measured NO_2 concentration. Seaton and Dennekamp[25] argue that ultra-fine particles may be this other pollutant. However, the relationship between NO_2 and ultra-fine particles is so close that it is impossible to distinguish their effects in epidemiological studies. It is also possible that no relationship between indoor NO_2 and asthma was found because there were fewer studies that had direct NO_2 measurements and study populations were usually smaller in these studies[15]. A large US study[26], not included in the 2013 meta-analysis, following 1342 children between 5 and 10 year old measured NO_2 during four one month long periods concluded that every 5 ppb (10 µg/m^3) increase in NO_2 exposure above a threshold of 6 ppb (12 µg/m^3) is associated with a 1,37 times higher risk of higher asthma severity score. Thus children exposed to NO_2 indoors are at risk for increased asthma well below the EU outdoor limit of 40 µg/m^3.

With regard to young children there is growing evidence linking combustion related outdoor air pollution with adverse brain development[27]. With regard to indoor air a Spanish study[11] from 2009 found an association between the presence of gas stoves and the concentration NO_2 during the first three months of life and the neuropsychological development at 4 years age. Early life exposure to household gas appliances was associated negatively with general cognitive functioning and with a higher risk of developing ADHD. A recent Chinese study[12] suggest that cooking during pregnancy is associated with an increased risk of hyperactive behaviours in children at around 3 years age. Moreover these risks were higher when mothers cooked frequently, or when the household used gas or solids fuels for cooking, or when the kitchen was poorly ventilated.

Adults

Epidemiological studies of the health effects to adults were reviewed in 2009 by WHO[8]. In comparison to the number of studies concerning children, there are relatively few studies on adults. Further the study results were not conclusive about a relation between long term exposure and respiratory illness. For example Jarvis[28] found that woman who reported that they mainly used gas for cooking had an increased risk of several asthma like symptoms and a reduction of the forced expiration volume compared to woman who did not a gas stove. These associations were not found with man. While Eisner[29] did not find an apparent impact of gas stove use on pulmonary function or respiratory symptoms at all.
With regard to short term exposure, human controlled exposure experimental studies indicate minor changes in pulmonary function in people with asthma exposed to 560 µg/m^3 nitrogen dioxide for up to 2,5 hour. These findings support the 1 hour guideline of 200 µg/m^3. A recent study examined the blood chemistry and cardiovascular changes of 12 healthy volunteers exposed to 90 minutes domestic gas cooking versus control (room air)[30]. This resulted in a 276 ppb increased NO_2 concentration in the air versus the control situation. Nitrite blood

levels were increased by 15% after 15 minutes. Further the blood pressure was lowered by 5 mm Hg from 45 minutes onwards. On short term the lowering of blood pressure may be a beneficial effect.

With Scopus (a scientific literature research tool) a search has been carried out towards European studies related to adults since 2009 containing ‘Health’, ‘Electric’ and ‘gas stove’ in title, abstract or keywords.
Only two studies were found. The first, a Polish study from 2018[31] indicated that use of cooking appliances with gas was correlated with 1,77 more frequent declarations of asthma both for children and adults. The second, a study in Lithuania has measured NO_2 during all seasons in 12 homes. It reported that the kitchen NO_2 concentration in homes cooking with gas stoves were 2,5 times higher compared to homes with electric stoves[32].

Widening the search by removing “Electric” delivered 395 studies. Most of them were related with LPG or biomass stoves and were left out. A Hongkong[33] study indicated that restaurant workers using electric cookers had significant better lung function than their gas using counterparts. Their mean Forced Expiration Volume (FEV) and Forced Vital Capacity were 5,4% and 3,8% higher, respectively.

Most of the relevant studies are related to the US[34,35,36,37,38,39,40,41]. These US studies are related to health costs, effect of range hoods, methane emissions and will be discussed in the next paragraphs.
One US study[42] highlighted the adverse effects of heating your home with a gas stove without ventilation. The odds rates for pneumonia and cough were twice as high as in homes where gas stoves were only used for cooking.

With regard to Europe only three additional papers have been found, indicating that in Europe compared to other countries research interest is relative low.

A Polish paper from 2018 indicated that in a kitchen by cooking on gas the acceptable NO_2 standards for working zones are exceeded[43]. A Romanian paper indicated a four times higher number of self-reported flu like symptoms in houses with a gas heater in the children’s bedroom[44]
A 2015 Italian[45] paper has investigated short-term respiratory effects due to the exposure of cooking generated aerosols. The reports support a potential link between short term exposure of cooking generated particles and woman’s respiratory inflammation responses.
In the winter of 2009 – 2010 in 16 Irish and Scottish homes cooking on gas NO_2 was measured[46]. The concentrations measured were on average 17 $\mu g/m^3$ and ranged between 4 and 46 $\mu g/m^3$.

Brain effects
Torkmahalleh[13] has assessed the effect of exposure to aerosol (both gases and particles) from indoor gas stove cooking on the nervous system with electroencephalography. Peak ultra-fine particle concentration due to 14 minutes of chicken frying was $3 \cdot 10^5$ particles/cm^3.
The neurologic responses were similar to early-stage Alzheimer’s disease patients. Based on the short post exposure period and the fact that the changes took place in the frontal lobes of the brain the authors argue it is more likely that the translocation of the particles to the brain took place through the olfactory pathway instead of via the blood circulation.

A similar neurologic response has been found when people were exposed to cooking aerosol from frying meat on an electric stove[47]. The peak ultra-fine particle concentration was here $2 \cdot 10^5$ particles/cm^3. In both studies (gas and electric) it was observed that the beta3 band brain wave decreased upon cooking and then increased 30 min after the cooking. However, the difference was that in the gas stove study both the decrease and increase were statistically significant and for the electric stove only the subsequent increase 30 minutes after the cooking was statistically significant.
Both studies suggest that chronically exposed people exposed to high concentrations of cooking aerosol might endure changes in brain functioning. This should be further studied, to assess whether cooking with gas hobs might be a potential risk factor for developing dementia.

Findings from outdoor air pollution research with regard to NO_2 and UFP
Compared to larger particles ultra-fine particles have higher deposition rates in the lower respiratory tract[48]. Ultra-fine particles may even penetrate the blood circulation and translocate to essentially to all organs[49]. Exposure to ultra-fine particles induces cough and worsens asthma[49]. It can cause cardiovascular disease, it can cause brain dysfunction, it is linked to diabetes, cancer and low birth weight[49]. Typical concentration of UFP in ambient air in rural areas is 2600 particles/cm^3, whereas a roadside concentration may be 50.000 with a mean global concentration[49] of 10.000 particles/cm^3. These outdoor concentrations are rather low compared to indoors when cooking on gas which can cause indoor peak concentrations[50]. up to 1.500.000 particles/cm^3 .

The EPA[51] 2016 *Integrated Science Assessment for oxides of Nitrogen – Health Criteria*, report gives evidence for asthma attacks and supports a causal relationship between short-term NO_2 exposure and respiratory effects. Evidence for development of asthma supports a likely to be causal relationship between long-term NO_2 exposure and respiratory effects. There is more uncertainty as to whether short-term or long-term NO_2 exposure is related to cardiovascular effects, diabetes, reproductive and developmental effects, total mortality, and cancer.

For the European Union the European Environment Agency (EEA) estimates that 40,400 premature deaths[52] are linked to NO_2. The EEA estimates that 94% of the European urban population is exposed to ambient NO_2 concentrations above the WHO 2021 guidelines. Four percent of the urban population is exposed to ambient concentrations above the EU standard[53].

Achukulwisut[9] reported that in 2015 globally 4 million new asthma cases could be attributable to NO_2 pollution annually. This burden accounts for 13% of the global incidence. Anenberg[20] reported 1.9 million new paediatric asthma cases in 2019 globally based on NO_2 outdoor pollution. Cooking[54] is the most important indoor source of NO_2 accounting for 25% (161.000 case) of the total of 637.000 yearly new cases of paediatric asthma attributable to NO_2 exposure in urban areas in China.

2.4 Concentrations due to gas cooking appliances

This report discusses the following indoor air pollutants:
- Nitrogen oxides (both NO and NO_2);
- Carbon monoxide (CO);

- Ultra-fine particles (UFP);
- Formaldehyde and;
- Methane (CH_4) leakages is discussed as it is a major greenhouse gas.

This paragraph starts with laboratory measurements of stoves flue gasses, these report the emissions in ng per J burned gas [ng/J]. After that the above mentioned air pollutants due to cooking on gas will be treated separately.

Gas stove and oven flue gas measurements

Singer[55] measured emission from 12 used gas stoves (cooktop/oven combinations) and one additional cooktop. The cooking appliances were cleaned prior to experimental evaluation to ensure that any observed pollutant formation was associated with fuel combustion and not the result of volatilization and/or oxidation of spilled food residues. For the cooktop burner sets, the lowest emitted 5 NO_2/J and the highest emitted almost 18 ng NO_2/J. The device with the highest nitrogen dioxide emission has also the highest formaldehyde and carbon monoxide emission, see Figure 1. However the Particle Number (PN) emissions did not follow the same pattern. There seems no relation between the gaseous emissions and the particle emissions. For the individual cooktops here was a large spread in Particle Number emission. This might have been caused by the operating conditions and recent use history.

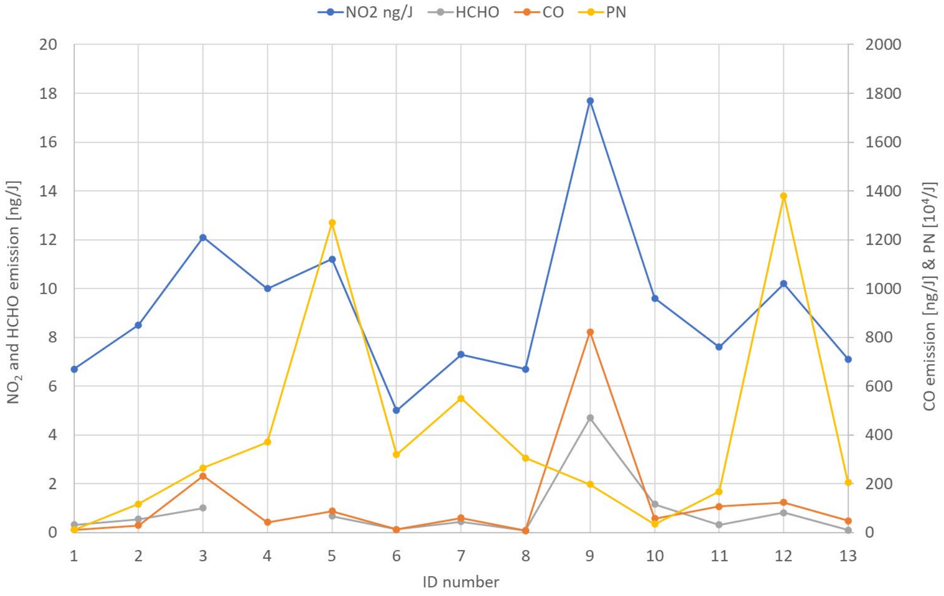

Figure 1 Comparison of NO_2 and HCHO (left axis) with CO and ultra-fine particle number (PN - right axis) emissions of 13 cooktop burners measured by Singer[55].

Singer[55] has also measured 12 gas ovens using the bottom burners of which the lowest emitted 4 and the highest emitted almost 14 ng NO_2/J. These emission values are comparable with the gas stoves. The device with the highest nitrogen dioxide emission has also the highest formaldehyde and carbon monoxide emission, see Figure 2. The ultra-fine particle number (PN) emissions does not follow this pattern. Comparable with the gas stoves there seems no relation between the gaseous emissions and the particle emissions. Also here for the individual ovens there was a large spread in Particle Number emission. The authors suggest that this might have been caused by the operating conditions and recent use history.

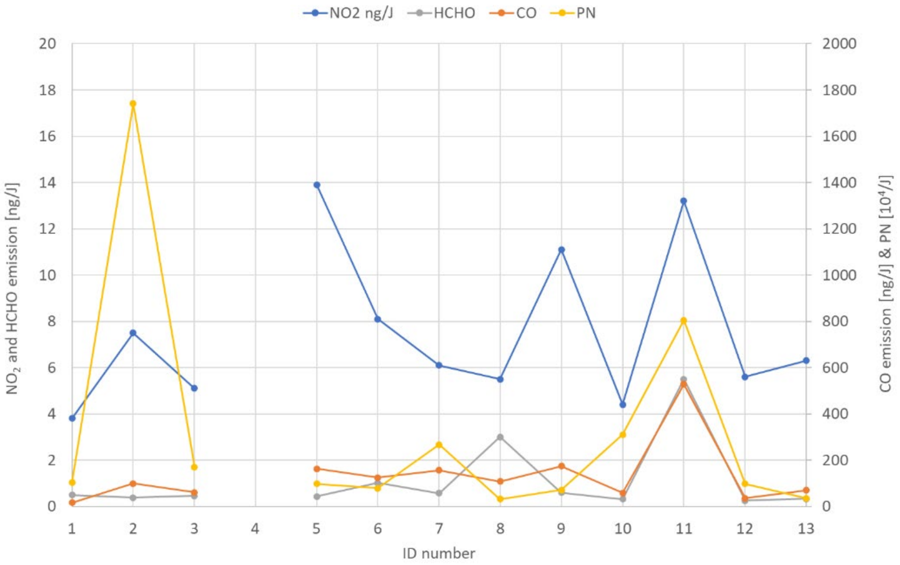

Figure 2 Comparison of NO_2 and HCHO (lef axis) with CO and ultra-fine particle number (PN - right axis) emissions of 12 oven bottom burners measured by Singer[55], no data were given for the oven with ID=4.

The gas cooktop/oven combinations varied in year of construction between 1992 and 2007. There was a weak correlation ($R^2 = 0,34$) between year of construction and NO_2 emission from the cooktop burners. For the oven correlation coefficients of 0,39 and 0,72 are found for respectively the bottom and broiler burners. This suggest that cooking on gas with new equipment may lead to higher indoor NO_2 concentrations compared to older equipment.

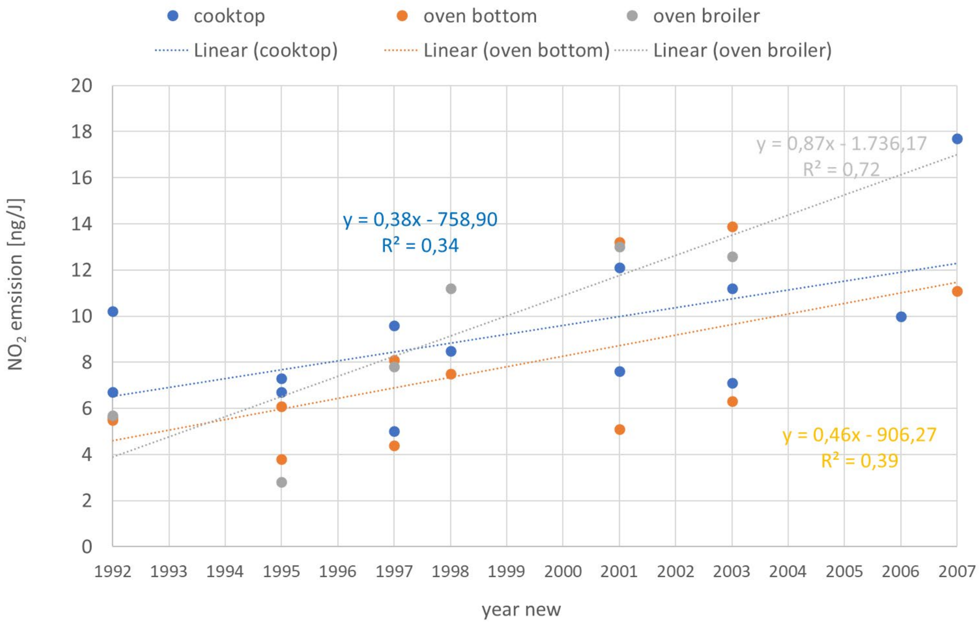

Figure 3 Analysis of effect of construction year of gas cooktop/oven combinations on NO_2 emission based on data measured by Singer[55].

Nitrogen dioxide (NO_2)

When cooking on 4 gas rings during 15 minutes Dennekamp[3] reached in the laboratory concentrations of 1900 µg/m^3 NO_2. Forty five minutes after turning off the rings the concentrations were still around 500 µg/m^3 NO_2, which is much higher than the EU ambient 1 hour limit value and the WHO guideline of 200 µg/m^3.

Appendix B lists NO_2 concentrations and source strengths that are derived from cooking on gas 4 typical Western European meals. These test were carried out by O'Leary[4] in the 26 m^3 TNO Indoor Air Quality laboratory under ventilation conditions meeting the Dutch Building Decree. Peak concentrations were in the order of 1100 µg/m^3 NO_2. The cooking time varied between 17 and 28 minutes. After that during 30 minutes the decay has been measured. The one hour average concentrations varied between 214 and 478 µg/m^3, thus all above the 1 hour limit value of 200 mg/m^3. In the same laboratory Jacobs[56] has measured NO_2 concentrations up to 358 µg/m^3 due to 10 minutes frying of 3 hamburgers in a pan.

Fortmann[57] has measured in a test house higher average and peak NO_2 levels (up to 1080 µg/m^3) due to use of the oven compared to the top burners. More recently Singer[58] measured pollutant concentrations from natural gas cooking burners without and with range hood in nine California homes. Without exhaust four of the nine homes had kitchen 1 h NO_2 exceeding the 200 µg/m^3. The highest 1 h NO_2 concentration was more than 500 µg/m^3.

In 2011 Delgado[59] has measured personal exposure in Birmingham with real time sensors with 5 minutes interval NO_2 peak level due to cooking up to 1500 µg/m^3. This peak value during cooking on gas was higher than the peak levels during commuting. The indoor/outdoor NO_2 exposure ratio in homes during cooking on gas (2.9) was clearly higher than in the absence of combustion sources (0,2 – 0,7). On average, subjects that cooked with gas appliances experienced higher 24-h personal exposures (56 ± 113 µg/m^3) than those that use electric hobs for cooking (35 ± 75 µg/m^3).

In field studies mainly passive samplers have been used, these samplers give an average value over measurement periods of typically 1 or 2 weeks. Year round measurements in with passive samplers in 12 Lithuanian houses with gas stoves and 5 houses with electric stoves showed that the concentration in the kitchen was by 2,5 times higher in kitchens with gas stoves than with electric stoves[32]. The highest indoor and outdoor concentrations were observed in the winter season and the lowest during summer. The highest concentration was found in the kitchen and the lowest in the bedrooms,. In none of the houses the EU annual limit value was exceeded, Due to the methodology used, which is passive sampling no conclusion can be drawn with regards to the EU 1 hour limit value exceedance. The 2021 WHO value of 10 µg/m^3 was exceeded in all houses equipped with gas stove, see Table 6. While houses equipped with electric stoves were around the guideline value of 10 µg/m^3, mainly due to infiltration of outdoor NO_2. The authors suggest that outdoor air has a greater influence on indoor levels in the bedroom than in other rooms. This is because bedrooms are here more ventilated than other rooms in the homes, their doors are more likely to be closed, compared to living rooms preventing mixing with NO_2 from indoor sources (i.e. gas appliances) and they are usually farthest from the kitchen.

The difference between summer and winter has also been observed by Paulin[37]. Mean duration of cooking time was longer in the cold versus the non-cold season. And when cooked with long duration, longer than 150 min/day, the 24 hour averaged summer and winter concentration were 67 and 377 µg/m^3 respectively. The difference may be caused by different ventilation patterns in addition to different cooking.

Mullen[60] has measured the impact of natural gas appliances in 352 California homes. Measurements were conducted using a package of passive samplers and monitors that were mailed to 323 homes and delivered by the researchers to 29 homes. More details about the study setup can be found in[61]. They estimated the effect of cooking on gas by subtracting the effect of the outdoor concentration by assuming an NO_2 infiltration factor of 0,4. More cooking led to higher concentrations in houses with gas cooking appliances, but not in homes with electrical cooking.

Zhao[62] has measured contaminants in 23 low-income apartments cooking on gas and compared the concentrations with California single family houses. While concentrations of $PM_{2.5}$ were similar and formaldehyde was 25% lower in apartments compared to houses with similar levels of cooking, NO_2 was 165% higher in the apartments. This indicates a higher risk from gas cooking in smaller spaces.

Table 6 Average NO_2 concentrations in dwellings when cooked on gas.

Author / country	location	period	NO_2 [µg/m^3]
Dedele[32] Lithuania	kitchen living room bedroom	Yearly	25,7 22,8 19,9
Morales[11], Spain	Living room	Yearly	

	• Electric stove • Gas stove		14 37
Delgado-Saborit[59], UK	Personal exposure - Electric stove - Gas stove	24 h	35 75
Non-European studies			
Mullen[60] US	Kitchen bedroom	6 days in heating season	18 14
Zhao[62]	Kitchen/living room	week	19*
Noris[63]	Kitchen/living room	2 weeks	77**

** Two apartments had a weekly NO_2 above 56 μg/m^3 (30 ppb).*

*** Five apartments equipped with cookstove with pilot burners.*

Carbon monoxide

Singer[55] has measured in the laboratory 13 ranges of which the lowest emitted 7 and the highest emitted 823 ng CO/J. The average value was 126 ng CO/J. The highest value might have been caused by a wrong orifice.

In the field study of Mullen the highest 1-h CO concentrations were higher in homes that cooked with gas and increased with amount of gas cooking and not using the kitchen exhaust fan. However, the average values for these situations, which ranged from 4 up to 7 mg/m^3, are much lower than the WHO 1-h AQG of 35 mg/m^3. In none of the 353 homes a value has been measured above the 1-h WHO indoor AQG.

Fortmann[57] has reported relative high CO values of 23 mg/m^3 (20 ppm) during a five hour self-cleaning oven test with a gas range. About half of this concentration occurred during oven cleaning with an electric range. These emissions with the electric oven were likely to the combustion of food materials on the surface of the oven.

Formaldehyde

Singer[55] has measured in the laboratory 13 ranges of which the lowest emitted 0,09 and the highest emitted 4,7 ng formaldehyde/J. The average emission was 0,85 ng/J. Assuming 0,6% CO_2 in the exhaust, the formaldehyde concentration in the exhaust flow ranged between 12 and 605 ppb. For most of the devices even the concentration in the exhaust flow was lower than the WHO AQG of 100 μg/m^3 (81 ppb).

Mullen[60] has measured the impact of natural gas appliances in 352 California homes. Formaldehyde in the kitchen was not significantly increased in homes with cooking on gas (17 ppb = 21 μg/m^3) compared to homes with electric cooktops (15 ppb = 18 μg/m^3). The average concentrations in the bedroom were respectively 21 and 17 μg/m^3 for these two groups. In only a very small fraction of the 352 homes the WHO indoor 30 minute guideline value of 100 μg/m^3 was exceeded. And also for these homes there was no difference between the kitchen and the bedroom, suggesting that the main source is from furniture.

Zhao[62] has measured formaldehyde in 23 low-income apartments cooking on gas and compared the concentrations with 70 California single family houses[64]. The mean formaldehyde concentration was 14 ppb (17 µg/m^3) in the apartments versus 19 ppb (23 µg/m^3) in the single family houses.

Based on these findings it can be concluded that the contribution of cooking to the formaldehyde concentration is rather low compared to emissions due to furniture. Therefore formaldehyde will not be considered further in this study.

Methane
Lebel[34] has determined in 53 homes the methane emission during cooking and non-cooking periods at respectively 259 and 57,9 mg/h. Assuming a ventilation of 12 dm^3/s the equilibrium concentration during non-cooking periods is about 1,3 mg/m^3 (2 ppm). During cooking this concentration is about 6 mg/m^3 (8 ppm). Lebel estimated that 0,8 - 1,3 % of the used gas is emitted unburned. Using a 20 year timeframe for methane, annual methane emissions from all gas stoves in US homes have a climate impact comparable to the annual carbon dioxide emissions of 500.000 cars.

Ultra-fine particles
Ultra-fine particles are defined as particles with a size smaller than 100 nm. Dennekamp[3] concludes that high concentrations of these particles are generated by gas combustion, by frying, and by cooking of fatty foods. Electric rings and grills may also generate particles from their surfaces. This type of emission did not occur when a pot of water was put on the ring. This might be explained by that the heat of the ring is being conducted to the water so that deposited material on the ring does not burn off. In experiments were gas burning was the dominant source of particles, most particles were in the size range of 15-40 nm. When bacon was fried on gas or electric rings the particles are larger, in the size range 50 – 100 nm. The smaller particles generated during experiments by Dennekamp[3] grew in size with time because of coagulation of small particles. Coagulation is the collision of two or more particles, sticking together and forming a larger particle. The number of small particles can also be reduced due to evaporation. Xue[65] showed that approximately 70% of the ultra-fine particles emitted by coking stoves are semi-volatile. But 30% are non-volatile and do not evaporate even under extremely high dilution conditions.

Wallace[66] reports particle production rates of 2 x 10^{14} particles/hour (3,3 x 10^{12} particles/min) over a typical cooking time of about 5 – 15 minutes frying. Most of the particles are in the ultrafine range, but the largest volume and thus mass is contributed by particles between 0,1 and 0,3 µm in diameter. The smallest measured particles of 10 nm had the highest decay rate of 5 – 6 per hour, mostly due to deposition by Brownian motion and partly due to the air exchange of about 0,4 per hour. The lowest decay rate is for 0,1 µm particles and amounts 1,5 per hour.
A follow-up study by Wallace[50] with equipment measuring up to 2 nm small particles indicated that peak concentrations from gas and electric stoves occur at a particle size of about 5 nm. Total number concentrations were as much as 10 times greater than reported in previous studies measuring particle size above 10 nm. About 95% of the particles at the beginning of the decay period had diameters smaller than 10 nm. Because of these high concentrations of very small particles coagulation was the dominant process after the source was turned off, leading to an equilibrium concentration of 1.500.000 particles/cm^3 after about five minutes burning. Forty

minutes after turning off the particle size increased from 5 to about 10 nm as deposition and coagulation depleted the numbers of the smallest particles.
The emission rate of particles smaller than 10 nm for boiling water with the gas stove was about 6 x 10^{12} particles/min while for the electric stove this was 1,5 x 10^{12} particles/min. The use of cooking oil while stir frying shifts the distribution towards larger particles with peak values occurring in the 16 – 20 nm range. However, the measured emission rates decreased when cooking oil was used. This may reflect the loss of detection efficiency that has been noted before for water-based CPC when challenged with oil droplets[67].

Italian research towards ultra-fine particle emission of burners for water heating with cook stoves showed that the cook stove emitted a larger amount of very small particles of about 3 nm since there post-oxidation is not possible[68]. In the water heaters these small particles were also formed in large numbers in the flame region but were also strongly oxidized in the post-oxidation region of the devices. This larger emission for cooking burners compared to water heating burner was also found by Singer[55].

An Italian field study[45] in 43 houses has measured a four times higher particle number during cooking typical Italian food on gas stoves (3,3 x 10^5 part/cm^3) compared to electrical stoves (9,0 x 10^4 part/cm^3). Each cooking event lasted about 2 hours and no special instruction on the type of food or method of cooking was given. The measurement were performed with a TSI CPC 3007 which is able to measure particles down to 10 nm.

Beko[69] has measured ultra-fine particles in 56 Danish homes with NanoTracers. Thirty-three homes were equipped with an electric stove and 23 with a gas stove. Two homes were equipped with a gas oven. Ultra-fine particles, 10 – 300 nm, were measured with a NanoTracer, which has an measurement accuracy of ±30%. Activities most strongly affecting UFP were related to cooking and candle burning. The total daily integrated exposure in houses with an electric stove was 526.000 cm^{-3} h/d (95% CI: 305.000 – 747.00) and in houses with an gas stove 868.000 cm^{-3} h/d (95% CI: 345.000 – 1.391.00). Although the exposure in house with gas stove is higher the difference is not significant. A possible reason might be that the presence of larger cooking particles, larger than 400 nm, can drastically reduce the accuracy of the NanoTracer[70]. Another explanation may be that although gas stoves due to the burning of gas emit more ultra-fine particles than electric stoves, the difference may not be significant due to high decay rates for these small particles due to coagulation. Another confounding effect may be that the pan temperature may differ between different users, which has a large effect on the ultra-fine particle emission rate during frying.

In Sweden a study toward ultra-fine particles in 22 houses during a week with Nanotracers and DiSC Mini and a comparison with outdoor concentrations has been carried out by Isaxon[71]. The average total integrated daily exposure was 400.000 cm^{-3} h/d. It was found that candle burning and activities related to cooking were the main particle sources. The type of cooking device was not specified. High levels, above 10.000 particles/cm^3, mainly occur during active periods of occupancy. In epidemiological studies it is not uncommon to estimate the exposure of an population based on measurements from one outdoor station. If this approach is used for indoor ultra-fine particles, the exposure estimation would be only relevant when no activities are conducted at home, i.e. mainly when people are asleep.

Shehab[6] et al (2021) measured concentrations of ultra-fine particles with a DiscMini in the houses of 40 subjects living in Birmingham (UK). The concentration of ultrafine-particles exposure measured during cooking with gas stoves (median = 17,439 part/cm^3) was significantly higher ($p<0.005$) than concentrations measured for subjects cooking with an electric stove (median = 3,184 part/cm^3) for those subjects living in houses located away from residential traffic sources. The corresponding mean values for UPF exposure were for persons during cooking on gas (40,711 particles/cm^3) and for those using an electric stove (14,812 particles/cm^3).

A large German[72] study in 40 households with Mobility Particle Size Spectrometers estimates the contribution of cooking to about 20% of the daily integrated exposure of ultra-fine particles. The particle emission rate due to frying was estimated at about 3×10^{11} particles per minute. Unfortunately, the type of furnace in the several houses was not reported in the study. The exposure in this study was much lower than in the Danish[69] study. The main reason was that the average candle burning time was here only 16 minutes per day while in the Danish study it was 140 minutes per day.

Bhangar[73] has measured in 7 Californian dwellings ultra-fine particles >6 nm. Unvented natural-gas pilot lights contributed up to 19% of the exposure. The most important source activity was cooking, and the frequency of cooking food on either a gas or electric range is therefore an important variable influencing exposure to ultra-fine particles in houses. Although the authors didn't report this as a finding, the source strength of 19 detected cooking activities in the five houses with a gas stove was with 48 [95% confidence interval: 33 – 63] x 10^{12} particles/min significantly higher than for the cooking activities within the two houses equipped with an electric stove 12 [2 – 22] x 10^{12} particles/min. However this difference may also be due to a difference in the cooking behaviour of the residents, e.g. frying on high temperature.

Singer[58] measured UFP concentrations larger than 6 nm with a TSI 3781 CPC in nine California homes. In all homes, the highest hourly integrated particle number exceeded 2×10^5 particles/cm^3-h, and the highest 4 hour particle number exceeded 3×10^5 cm^3-hr in the kitchen.

2.5 Effect of measures

Replacement of gas stove by electrical stove

Electric cooking does not contribute to NO_2 emissions. Assuming there are no other sources of NO_2 emissions such as smoking or burning incense in the kitchen a 100% indoor NO_2 emission reduction can be made by replacing gas stoves by electrical stoves.

Stove replacement in Baltimore city by Paulin[74] resulted in a 51% and 42% decrease in median NO_2 concentration at 3 months of follow-up in the kitchen and the bedroom. The reduction was not high, most probably caused by the relative high outdoor NO_2 concentration of 55 µg/m^3.

Colton[75] reported a 65% lower NO_2 concentration after families moved to green houses compared to moving to conventional houses. In the green houses 100% electric cooking was applied, while in the control group 93% was cooking on gas.

Replacement of pilot burners by electronic ignition
In the US gas stoves with pilot burners are often being used. These continuous burning burners can lead to high average NO_2 concentrations in the order of 40 to 50 µg/m^3. Replacement of these stoves with pilot burners with stoves with electronic ignition, addition of range hoods that vented to outside and an increase in the apartment ventilation lead to NO_2 reductions of 58%[63]. This replacement might also decrease ultra-fine particle exposure by 19%[73].

Range hood
Field studies towards the effect of range hood are not conclusive. Despite in some studies no or even a detrimental effect on nitrogen dioxide concentration have been reported, positive health effects have been reported in other studies.

A study[28] in the UK reported that 27% of the woman who reported using gas for cooking reported they had an extractor fan. About 60% had an extractor fan taking cooking fumes to outside. However they had the same increase in the reporting of symptoms as those who did not. Even if woman reported that they used the extractor most of the time, no protective effect has been observed compared with woman who had no extractor fan or used it infrequently.

An US study[39] conducted with children aged 2 – 16 years who lived in houses were gas stoves were used indicated that the prevalence of asthma, wheeze and bronchitis were lower among children whose parents used ventilation compared to children whose parent reported not using ventilation when operating gas stoves. Ventilation was characterized as having an exhaust fan near the stove that sends fumes outside the home. The study reported also a number of parents that used the cook stove also for heating their home. Not using the stove for space heating and using ventilation lowered the odds on asthma by 59%.

Paulin[74] tested the effect of the installation of a range hood in Baltimore City (US). The hood capacity according to the manufacturer was 272 – 462 m^3/hour. No reduction was measured, but instead a non-significant increase after instalment of a range hood. It was unclear if the lack of efficiency was due primarily to lack of use of the hoods as this was not monitored. In a German study the range hood was turned on during 29% of the cooking rated activities[72]. In a US study[76] this percentage was between 28 and 36% for respectively apartments and houses. A Danish study[77] indicated that only 6,4% of the households had a hood and used it often or always. A Canadian[78] study indicated that only 26% of the cooking activities were conducted with added ventilation: range hood use 10%, window opening 15% and both 2%. Of the 132 households 35 had a ducted range hood and 15 had a unvented (recirculation) hood. Further the effect of range hood is larger for the back burner then for the front burner[41].
It may also be possible that in some houses the instalment of the hoods increased the ventilation with outdoor air, also when not being used. If the outdoor air is polluted, then the outdoor air would be a source of indoor pollution indoors. This was observed in Baltimore City, where the relative high ambient concentration led to additional infiltration of NO_2.

A third reason of rangehoods not being effective may be that the measured air flows are often lower than product specifications[62,79].

Since cooking with electric burners also produces pollutants like $PM_{2.5}$, kitchen exhaust ventilation should be available in all homes and operated as a precaution whenever cooking occurs[58].

Recirculation hood with activated carbon filter
In the Netherlands it has been estimated that about 50% of the hoods currently being sold are recirculation hoods. In a German[72] exposure study under 40 households 28% did not have a hood, 50% had a recirculation hood and only 22% had a hood vented to outside. Recirculation hoods are especially popular in apartment buildings as it is often not permitted to make your own vent to outside for a hood. Initially a recirculation hood with a new activated carbon filter can reduce the NO_2 peak concentration with 67%, see Figure 4.

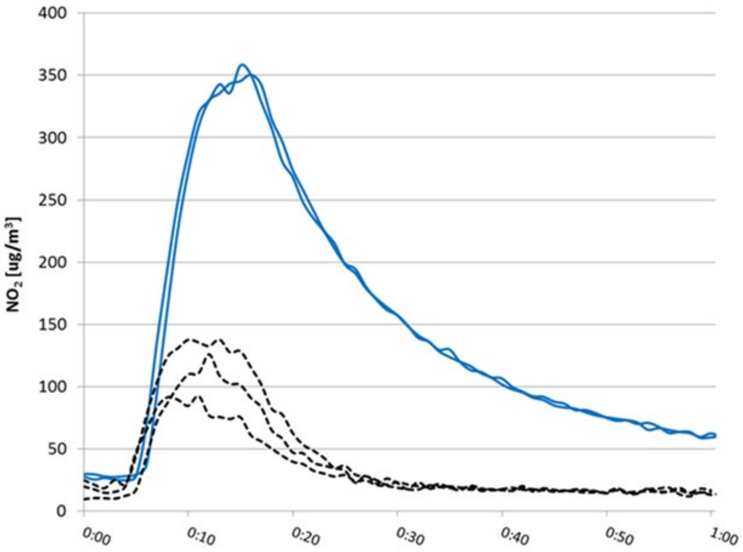

Figure 4 Measured NO_2 concentration due to 10 minutes frying of 3 hamburgers on one pit with (black dashed line) and without (blue line) activated carbon filter[56].

However an aging test performed on this carbon filter of the recirculation hood simulating cooking on gas (20 minutes/day 5 kW) showed an initial NO_2 reduction of 56%. After 19 days of use this reduction dropped to only 19%, see Figure 5. Even with a new fresh filter the hourly average NO_2 concentration was here above the WHO indoor air 1-hour air quality guideline.

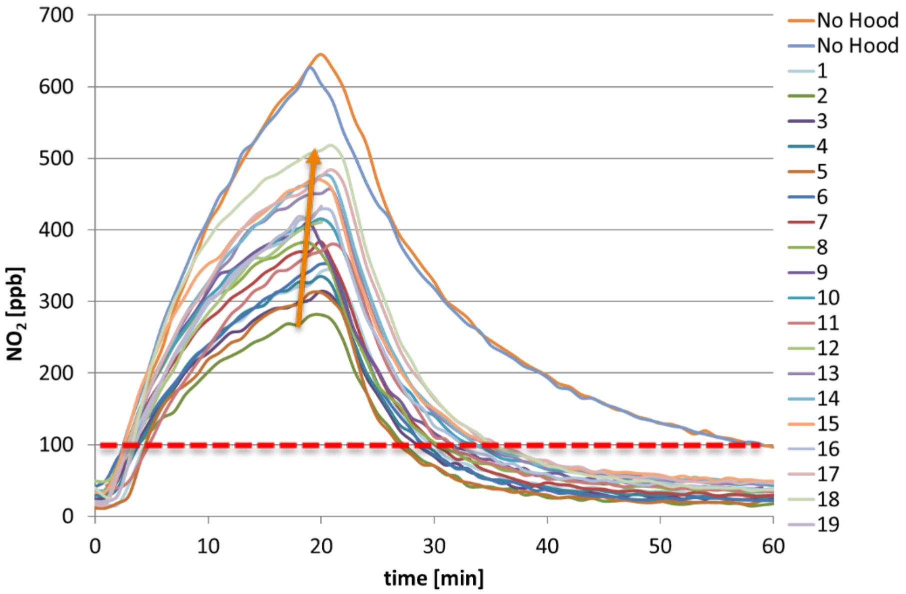

Figure 5 TNO 26 m^3 IAQ laboratory, measured NO_2 concentration due to 15 minutes gas burning on 3 pits, total power 5 kW[56]. The first two measurements have been executed without active carbon filter. Note that concentrations are in ppb. The WHO indoor Air Quality Guideline of 200 µg/m^3 (±100 ppb) is indicated with the red dashed line.

These results are in line with Paulin[74] who found a 27% reduction due to the placement of air purifiers with carbon filter in the kitchen. It further has to be noted that a optimised absorption filter may solve the NO_2 problem, but that also the ultra-fine particles should be captured. It is assumed that for this a highly efficient filter should be necessary. Such an filter introduces additional pressure drop, a higher noise level and would require frequent replacement.

Plasma filters
Recirculation hoods are equipped with carbon filters to remove odour. An disadvantage is that the carbon filters require regular replacement. Plasma filters claim that they do not need this replacement and are therefore becoming more and more popular. Jacobs[56] has tested one product of a commercially available plasma filter in combination with a gas stove. When using the plasma hood the NO_2 peak concentration increased from 350 to 667 and 1155 ug/m^3 (duplicate measurements). This can be explained by the fact the plasma hood also generates ozone. Thereby NO is converted to NO_2 and possibly also nitrogen from the air turned over to NO_2. This is supported by the variation in time of the gaseous compounds as shown in Figure 6. Plasma filters are normally used in combination with electric stoves. However, it should be noted that not all suppliers of plasma filters do explicitly warn against the use of this filter in combination with cooking on gas.

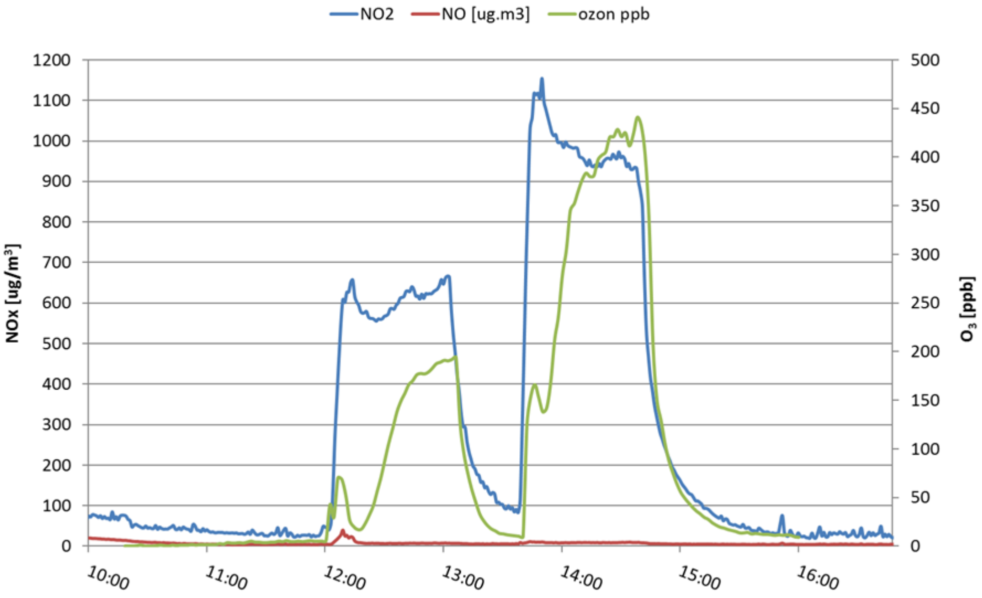

Figure 6 TNO 26 m^3 IAQ laboratory, NO_x and ozone concentration with plasma hood during frying of three hamburgers, experiment in duplicate.

2.6 Health costs associated with gas cooking appliances

For the 28 European member states (EU 28) the annual costs of healthcare and lost productivity due to asthma, based on 2011 cost data, are estimated at EUR 19.5 and 14.4 billion[80]. The monetized value of 697,000 Disability Adjusted Life Years (DALYS) lost based on WHO 2011 data is estimated at EUR 38.3 billion. For asthma the total cost per patient per year were estimated at EUR 7443[80]. The total costs in 2011 involved with asthma for EU28 was estimated at EUR 72.2 billion.
A more recent estimate by the International Respiratory Coalition[81] for the societal cost of asthma was 48 billion euro for the EU27 and 14 billion euro for the UK based on 2019 data and a dollar-euro rate of 1. This estimate is based on the monetized Disability-adjusted life years (DALY) and is calculated as the product of the number of DALY and the Gross Domestic Product (GDP) per capita.

For the EU27 the population attributable fraction (PAF) of paediatric asthma diagnosed by a doctor due to gas stoves amounts 7.3% (see paragraph 2.3). In the UK, where the number of households cooking on gas is higher than the EU average, 11.5% of paediatric asthma cases be avoided when the risk factor cooking on gas is removed. Asthma is assumed to be a chronic disease, thus most children having asthma due to cooking on gas end up as adults having asthma. Therefore the PAF multiplied with the societal cost due to asthma is a good predictor for the health cost associated with gas cooking appliances.

EU 27: 0.073 x 48 billion = 3.5 billion/year
UK: 0.115 x 13,8 billion = 1.6 billion /year

To bring this into perspective this represents 25 euro per year for the EU resident and 47 euro per year for UK residents exposed to gas cooking.

Paulin[37] reported that children living in homes with higher 24 hour averaged nitrogen dioxide concentrations due to cooking on gas, reported increased use of asthma rescue medication in the evening/night following exposure.
A US modelling study[40] towards the effect of energy reduction in houses by tightening the building envelope indicated that this could lead to a 20% increase in serious asthma events. The estimated additional health care cost due to weatherization were about $300 per year per asthmatic patient, mainly due to additional medication. While based on the model, changing the gas stove to an electric one could save $180 per year per asthmatic patient. A more recent modelling study from 2021[35] indicated that retrofits lead to overall better health outcomes and comparable healthcare cost savings if reduced air exchange due to energy saving air tightening is compensated with mechanical ventilation according to the ASHRAE standard. Switching to electrical cooking was not mentioned in this study.

3 Simulation study

3.1 Approach

TNO conducted a computer simulation study using the multizone home air flow model called COMIS. This simulation study is intended to determine the NO_2 exposure in dwellings and conditions representative for Southern, Eastern and Western EU countries and the UK. With this study trends such as the effect of energy transition, the use of hoods and the effect of gas cooking vs. electric have been simulated. The input parameters such as NO_2 emission/5 minutes, average duration of gas stove use per day, availability of range hoods and effectiveness, ventilation flow and air tightness/infiltration NO_2 from outdoor air and deposition of NO_2 on surfaces have been derived as much as possible from peer reviewed articles and literature such as JRC technical report[82] about cooking appliances.

Simulation variables include:

- Air quality with gas cooking under the business as usual / current situation;
- Air quality after retrofitting with increased air tightness;
- Changes to air quality when using an extraction hood;
- Changes to air quality when switching from gas to electric cooking.

3.2 Model description

Housing characteristics

In order to show the effect of housing characteristics, four typical kitchen characteristics have been defined, see Table 7.

Table 7 Housing characteristics typical for Southern, Eastern and Western EU countries and the UK for the current situation.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Volume [m^3]	60[83]	100*	100[84]	30[85]
Ventilation system	Natural*	Natural*	mechanical[84]	Natural*
Ventilation flow [dm^3/s]	-	-	6[84]	-
Ventilation during cooking [dm^3/s]	-	-	21[84]	-
Infiltration [dm^3/s]	9*	6*	6[84]	6*
Infiltration during cooking [dm^3/s]	9*	6*	0[84]	6*
Cooker hood	no	no	no	no

* *These values were estimated based on TNO buildings experts consulted for this simulation.*

As much as possible, literature has been sought to support the figures in Table 7. However for some aspects like the ventilation and infiltration flows, expert estimates have been used (see values marked with an *). For all regions after retrofitting an increased air tightness is assumed, reducing the infiltration contribution to the ventilation flow to 3 dm^3/s.

The Southern Europe and UK kitchen are modelled to be closed kitchens. While the Eastern and Western Europe are assumed to be open kitchens, thus including the volume of the living room.

Effect of cooker hood and electrical cooking
For the current situation it is assumed in Table 7 that no hood is present. This assumption has been made as many people, especially those who rent a house, do not have a hood. Or if they have one, it might be a recirculation hood which is hardly effective with regard to NO_2. In the case the hood vents to outside, it is often not being used, see also paragraph 2.5 .
For the simulation variant with an effective hood an effectivity of 55% is assumed[79] in combination with a mechanical exhaust flow through the hood of 62 dm^3/s. This means that in the emission schemes (Table 13) the emission of NO_2 has been reduced with 55%. Switching to electrical cooking reduces the NO_2 emission by 100%.

Outdoor air quality
For the outdoor NO_2 concentration a differentiation has been made between rural areas and cities, see Table 8. To investigate the effect of an high outdoor concentration for Western Europe and the UK areas with a rather high NO_2 concentration have been chosen, which only is relevant to dwellings near very busy roads. This will be an overestimate for the 'average' house in these regions.

Table 8 Yearly outdoor air NO_2 concentration based on the Urban NO_2 atlas[86].

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
City/rural	rural	rural	city	city
NO_2 concentration ($\mu g/m^3$)	10	20	40	50

NO_2 emission data
Singer has measured 13 ranges of which the lowest emitted 5 and the highest emitted almost 18 ng NO_2/J. Lebel measured in 32 homes emissions with a much narrower distribution. The 95% confidence interval (CI) was between 7,1 and 8,4 ng/J. For the simulations the average value of Singer and Lebel was used, namely 8,5 ng/J. Lebel concludes that the emissions are linearly related to the amount of natural gas burned. Assuming an heating value of 35 MJ/m^3 of gas (typical for the Netherlands), the emission rate is 0,3 mg NO_2 per litre of burned gas.

As mentioned earlier, Appendix B presents source strengths which are derived from unpublished results from cooking four typical West European meals carried out by O'Leary[4] in the TNO Indoor Air Quality laboratory. These source strengths are comparable with those mentioned in literature, see Table 9. Based on the four meals, it might be concluded that the type of meal has a comparable effect on the emission of NO_2 per J as the type of range top burner.

Table 9 NO_2 source strength due to cooking on gas cooktops [95% confidence interval].

Source	**NO_2 production [ng/J]**	**remarks**
Cooking of 4 litre water Singer 2009[55]	9,2 [7,5 - 10,9]	Laboratory measurements in flue gas stream for 13 different cooktop burners
4 complete meals, based on O'Leary 2019[4]	9,7 [9,0 - 10,4] 10,6 [10,3 - 10,9] 13,1 [11,7 – 14,5] 8,3 [7,3 – 9,4]	Laboratory chamber measurement with correction according to Ott for deposition and ventilation
Burning without a pan present Lebel 2022[34]	7,8 [7,1 – 8,4]	Chamber measurement with correction for ventilation in 32 homes

For ovens the source strength could not be retrieved from the Singer 2009 report. For ovens the source strength during the preheat phase and the cycling mode are based on Lebel[34].

Deposition

The effect of the NO_2 deposition rate has been included as simulation variable as this factor has an large influence. The deposition rate varies with humidity and surface characteristics[87]. The NO_2 binds with surface materials and is conversed to NO which is released to the gas phase. It can also be conversed to nitrite (NO_2^-) and nitrate (NO_3^-) ions, which remain bound to the surface. Logue[88] has performed simulations with an deposition of 0,5 and 1,0 per hour. Here the simulations were carried out with the average value of Logue, thus an deposition of 0,75. This is also in line with Fabian[89] who has used an deposition of 0,87 per hour for modelling.
A deposition rate of 0,75 per hour for a kitchen with a volume of 60, 100, 100 and 30 m^3 corresponds with a ventilation flow of clean air of respectively 13, 21, 21 and 6 dm^3/s. As shown in Table 7, the deposition flow rate equivalent is equal or larger than the combined ventilation/infiltration flow of respectively 9, 6, 12 and 6 dm^3/s (see Table 7) and it should be noted that the infiltration flow also contains ambient NO_2 concentrations.

Table 10 Comparison of effect NO_2 deposition rate and ventilation/infiltration flow in kitchens for this simulation.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Assumed volume for kitchen or kitchen & lounge	60	100	100	30
Ventilation flow rate equivalent to a NO_2 deposition rate of 0,75/hr [dm^3/s]	13	21	21	6
Ventilation + infiltration flow [dm^3/s]	9	6	12	6

Cooking behaviour

For the cooking behaviour data has been extracted from a JRC 2021 report[90] which is based on an online survey in 5100 households. The EU countries involved in the survey were: Czech Republic, Finland, France, Germany, Hungary, Italy, Poland, Romania, Spain, Sweden and Ireland. According to this investigation 31% of the households use gas stoves to cook. This percentage coincides very well with the Eurostat[17] percentage of 31,7% for 2020.

Table 11 shows that the average number of cooked meals is rather constant over the different European regions. However the duration of gas hob use per day is shorter in Western Europe.

Table 11 Average number of cooked meals and duration of gas hob use, between brackets reference is made to the figure number or the country in the JRC report[90].

	Southern Europe	**Eastern Europe**	**Western Europe**
Average number of cooked meals per person per week (fig 69)	11.6 (It) 9.8 (Sp)	9.3 (Ro) 8.9 (Po)	10.3
Duration of gas hob use per week [h] (fig 112)	4.8 (It) 4.2 (Sp)	4.8 (Ro) 4.2 (Po)	2.9

Table 12 indicates that in Eastern Europe the percentage gas fired ovens is much higher than in the other regions. Also the frequency of use and the duration of use are the highest in Eastern Europe.

The average duration of use of ovens seems quite long. Especially taken into account the time employed for making pizza’s and quiches (see table 29 in JRC report) that requires an oven time of typically 20 – 30 minutes.

Table 12 Oven type and use, between brackets reference is made to the figure number or the country in the JRC report[90].

	Southern Europe (Italy/Spain)	**Eastern Europe (Romania/Poland)**	**Western Europe (France)**
% of gas ovens (figure 77)	16.1 (It) 5.4 (Sp)	64.3 (Ro) 16.5 (Po)	13.5
Frequency of use [per week] (fig 82)	3.6 (It) 3.0 (Sp)	4.8 (Ro) 3.1 (Po)	3.9
Duration of use [h per week] (fig 95)	6.1 (It) 6.4 (Sp)	7.9 (Ro) 6.8 (Po)	5.4

Emission schemes

Based on the cooking behaviour and the NO_2 emission data four emission schemes have been set up for Southern, Eastern and Western Europe and the UK, see Table 13. For the gas consumption of the meals we use the meals defined by O’Leary[4] for typical Dutch meals. For these meals the gas consumption has been accurately measured, see Appendix B.

For breakfast and lunch the boiling of 0.8 litre of water is assumed for making tea. With 40% heating efficiency[91] this requires 20 litres of gas. For Southern Europe during lunch the warm meal is prepared. For Southern and Western Europe, we assume no cooking is done on Saturday. For Eastern Europe and the UK on

Wednesday and Saturday it is assumed that an oven dish is being made. For the UK an oven duration of 30 minutes and for Eastern Europe an oven duration of 75 minutes is assumed.

The gas consumption for cooking in Western Europe according to the emission scheme amounts 108 litre/day. This coincides reasonably well with the amount of 37 m^3 per year for cooking on gas as indicated by the Dutch information supplier for sustainable development Milieu Centraal[92], especially as no holiday leave has been taken into account.

Assuming a cooking time of half an hour the NO_2 emission coincides well with the value of 56 μg/s used by Fabian[89] for modelling.

Table 13 Emissions schemes for Southern, Eastern and Western Europe and the UK. Assuming an emission of 0,3 mg NO_2 per litre burned gas.

Southern Europe	litres of gas		
	breakfast	**lunch**	**dinner**
Monday	20	115	20
Tuesday	20	110	20
Wednesday	20	103	20
Thursday	20	57	20
Friday	20	103	20
Saturday	20		20
Sunday	20	110	20
	140	598	140

mg NO_2			
	breakfast	**lunch**	**dinner**
Monday	5,95	34,21	5,95
Tuesday	5,95	32,73	5,95
Wednesday	5,95	30,64	5,95
Thursday	5,95	16,96	5,95
Friday	5,95	30,64	5,95
Saturday	5,95		5,95
Sunday	5,95	32,73	5,95

Eastern Europe	litres of gas		
	breakfast	**lunch**	**dinner**
Monday	20	20	115
Tuesday	20	20	110
Wednesday	20	20	426
Thursday	20	20	57
Friday	20	20	103
Saturday	20	20	426
Sunday	20	20	110
	140	140	1348

mg NO_2			
	breakfast	**lunch**	**dinner**
Monday	5,95	5,95	34,21
Tuesday	5,95	5,95	32,73
Wednesday	5,95	5,95	125,51
Thursday	5,95	5,95	16,96
Friday	5,95	5,95	30,64
Saturday	5,95	5,95	125,51
Sunday	5,95	5,95	32,73

Western Europe	litres of gas		
	breakfast	**lunch**	**dinner**
Monday	20	20	115
Tuesday	20	20	110
Wednesday	20	20	103
Thursday	20	20	57
Friday	20	20	103
Saturday	20	20	
Sunday	20	20	110
	140	140	598

mg NO_2			
	breakfast	**lunch**	**dinner**
Monday	5,95	5,95	34,21
Tuesday	5,95	5,95	32,73
Wednesday	5,95	5,95	30,64
Thursday	5,95	5,95	16,96
Friday	5,95	5,95	30,64
Saturday	5,95	5,95	0,00
Sunday	5,95	5,95	32,73

UK	litres of gas		
	breakfast	**lunch**	**dinner**
Monday	20	20	115
Tuesday	20	20	110
Wednesday	20	20	170,5
Thursday	20	20	57
Friday	20	20	103
Saturday	20	20	170,5
Sunday	20	20	110
	140	140	836

mg NO_2			
	breakfast	**lunch**	**dinner**
Monday	5,95	5,95	34,21
Tuesday	5,95	5,95	32,73
Wednesday	5,95	5,95	50,72
Thursday	5,95	5,95	16,96
Friday	5,95	5,95	30,64
Saturday	5,95	5,95	50,72
Sunday	5,95	5,95	32,73

3.3 Results

Figure 7 through Figure 10 show the simulated NO_2 concentration for a week due to cooking on gas and outdoor sources for the current situation for Southern, Eastern and Western Europe and the UK. They assume a NO_2 deposition rate of 0.75 per hour. Figure 11 compares the simulated NO_2 concentration in greater detail during the first day for the different regions.

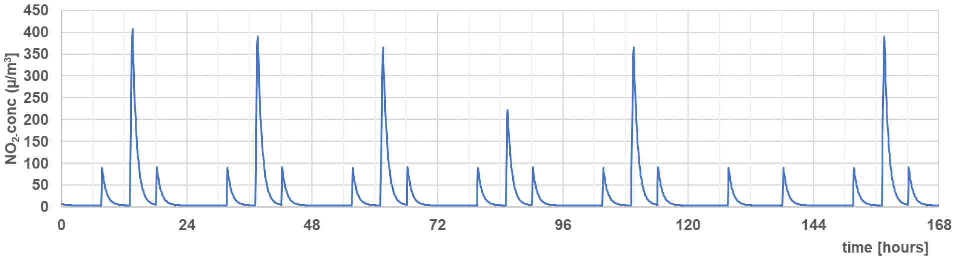

Figure 7 Simulated NO_2 concentration for South Europe during 1 week.

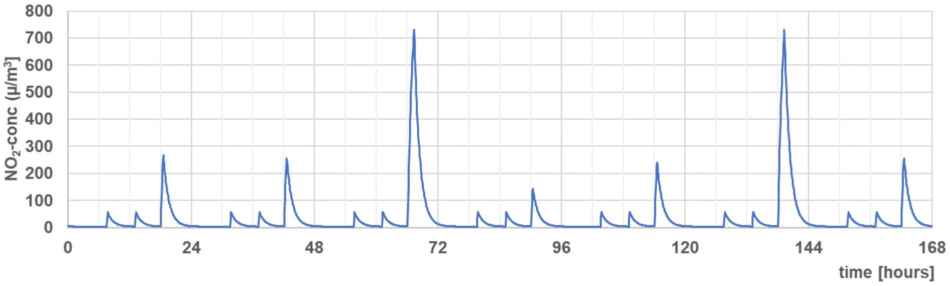

Figure 8 Simulated NO_2 concentration for Eastern Europe during 1 week.

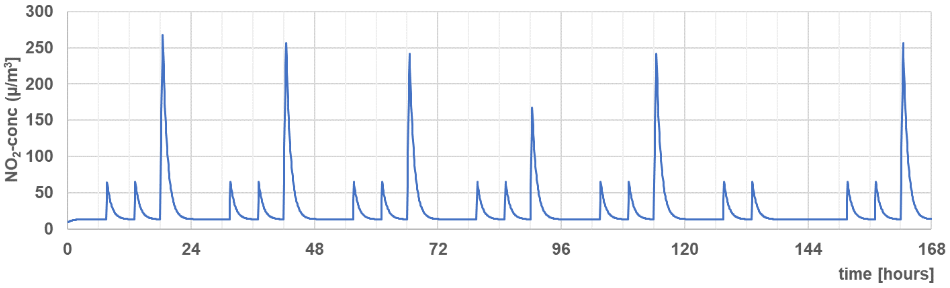

Figure 9 Simulated NO2 concentration for Western Europe during 1 week.

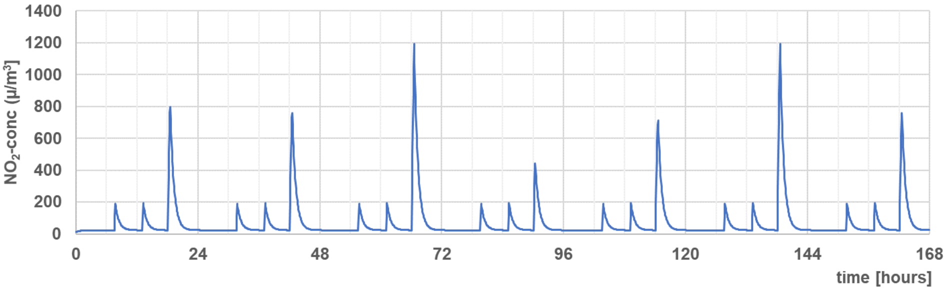

Figure 10 Simulated NO2 concentration for the UK during 1 week.

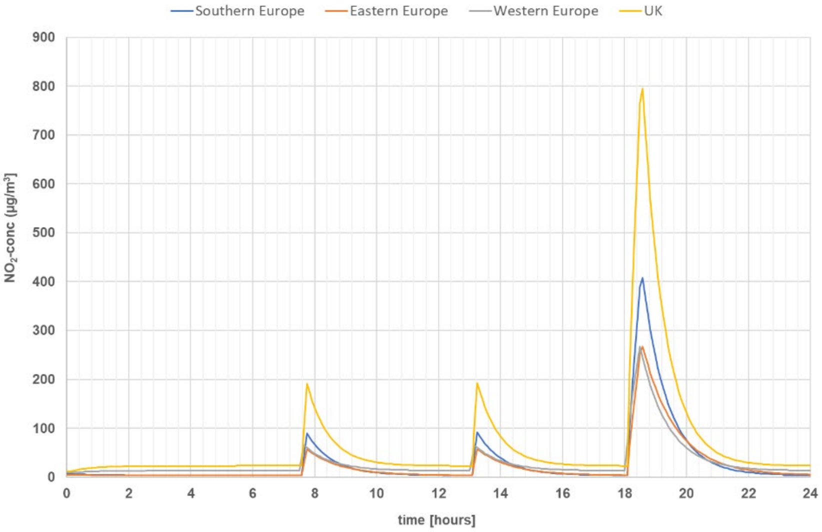

Figure 11 Comparison of simulated NO_2 concentration for Southern, Eastern and Western Europe and the UK during the first day:2 times boiling 0.8 litre water and meal 1. To facilitate the comparison, meal 1 for Southern Europe has been scheduled in the evening instead during lunch time.

Table 14 till Table 17 summarise the results with regard to the weekly average and maximum concentration. The background concentration is the concentration in the dwelling due to infiltration of outdoor air. The background NO_2 concentration is lower than the ambient concentration due to deposition and reaction of NO_2 on surfaces. The increase in NO_2 concentration due to cooking is calculated by subtracting the background from the weekly average.

The results of the simulations are checked on exceedance of the following:
- 10 µg/m³ – the WHO annual average guideline;
- 25 µg/m³ – the WHO daily average guideline;
- 40 µg/m³ – EU Ambient Air Quality Directive (2008/EC/50) annual Limit Value;
- 200 µg/m³ – EU Ambient Air Quality Directive (2008/EC/50) hourly Limit Value.

The simulations are executed with a deposition rate of 0.75 per hour. Appendix A lists the results for the current situation for deposition rates of 0.5 and 1 per hour.

Table 14 Summary of NO_2 simulation results for the current situation, deposition 0.75 per hour.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	24	34	27	68
Maximum [µg/m^3]	408	730	268	1192
Background [µg/m^3]	3.9	3.7	13	23
Increase by cooking [µg/m^3]	**20**	**30**	**13**	**45**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*No (5*)*	*No (2*)*	*No (5*)*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*No*
Below EU hourly 200 µg/m^3	*No (5**)*	*No (7**)*	*Yes*	*No (15**)*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

Table 15 Summary of NO_2 simulation results after retrofitting with **increased air tightness**, deposition 0.75 per hour.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	30	35	25	75
Maximum [µg/m^3]	446	770	266	1290
Background [µg/m^3]	1.6	1.7	11	15
Increase by cooking [µg/m^3]	**28**	**34**	**14**	**60**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*No (5*)*	*No (2*)*	*No (5*)*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*No*
Below EU hourly 200 µg/m^3	*No (5**)*	*No (9**)*	*Yes*	*No (16**)*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

Table 16 Summary of NO_2 simulation results after **applying a range hood**, deposition 0.75 per hour.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	11	13	19	35
Maximum [µg/m^3]	118	164	110	230
Background [µg/m^3]	4	3.7	13	23
Increase by cooking [µg/m^3]	**7**	**10**	**6**	**11**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*Yes*	*Yes*	*Yes*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*Yes*
Below EU hourly 200 µg/m^3	*Yes*	*Yes*	*Yes*	*Yes*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

Table 17 Summary of NO_2 simulation results after **switching to electrical cooking**, deposition 1 per hour.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	3.9	3.6	13	23
Maximum [µg/m^3]	7.2	5	13	23
Background [µg/m^3]	3.9	3.6	13	23
Increase by cooking [µg/m^3]	**0**	**0**	**0**	**0**
Below WHO annual 10 µg/m^3	*Yes*	*Yes*	*No*	*No*
Below WHO daily 25 µg/m^3	*Yes*	*Yes*	*Yes*	*Yes*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*Yes*
Below EU hourly 200 µg/m^3	*Yes*	*Yes*	*Yes*	*Yes*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

3.4 Limitations

A limitation of the model is that the yearly outdoor concentration is simulated as a constant value. Therefore due to switching to electrical cooking the simulation predicts no exceedances of 200 µg/m^3. In reality the outdoor concentration is not constant and under exceptional outdoor conditions such as summer smog or winter inversion conditions the indoor concentration might reach this level.

4 Discussion research questions

4.1 What are the measured concentrations due to gas cooking appliances?

Laboratory studies[3] simulating worst-case scenarios measured peak NO_2 concentrations up to 1900 µg/m³ NO_2. Cooking typical Western European meals in a 26 m³ laboratory led to peak concentrations of 1100 µg/m³ NO_2. The one hour average concentrations varied between 214 and 478 µg/m³ (see Appendix B). In a panel study[59], subjects cooking with gas appliances reported average 24-h concentrations of 56 ± 113 µg/m³, with maximum concentrations during cooking reported to be as high as 1500 µg/m³. All these concentrations are well above the 1 hour WHO and EU limit value of 200 mg/m³. The 24-h average exposure reported for the participants in the panel study is twice the recent 2021 WHO 24-h air quality guideline (25 µg/m³).

In field studies mainly passive samplers have been used, these samplers give an average value over measurement periods of typically 2 weeks. In houses equipped with gas stoves the highest nitrogen dioxide concentration is typically found in the kitchen and the lowest in the bedrooms. Average nitrogen dioxide values in the kitchen are typically 2,5 times higher in kitchens with gas stoves than with electric stoves. More cooking leads to higher concentrations in houses with gas cooking appliances, but not in homes with electrical cooking. Electric stoves don't produce NO_2 - so that homes with electric stoves are having NO_2 from other sources (infiltration from outdoor air, smoking, etc). NO_2 was 165% higher in the apartments compared to single family houses[62]. This indicates a higher risk from gas cooking in smaller kitchens.

4.2 Number of EU / UK households that exceed the WHO and European limit values due to gas cooking appliances

Of the population of 512 million in the EU27 + UK, about 180 million persons (35%) are exposed to emissions due to cooking on gas[17]. Based on our simulation results these 180 million citizens will be exposed to indoor NO_2 values not meeting the yearly WHO limit value of 10 µg/m³ and a large part is not meeting the EU outdoor 1-hour Limit Value of 200 µg/m³. Cooking on gas assuming average cooking behaviour, average kitchen dimension, average ventilation behaviour and without applying a range hood will lead to a situation in which the yearly WHO guideline value of 10 µg/m³ is exceeded indoors by about a factor two to three. In cities with high outdoor NO_2 concentrations even up to a factor of seven indoor exceedance can occur according to the simulations.

The daily average NO_2 WHO guideline value of 25 µg/m³ is exceeded in all four simulations, in Eastern Europe simulation 2 days per week and the simulation for the UK, with high ambient concentration, even 7 days per week.

The EU outdoor maximum 1-hour Limit Value of 200 µg/m³ may be exceeded only 18 hours per year. Only in the simulation for Western Europe, simulating an open kitchen with mechanical ventilation, this is not exceeded. In Eastern Europe, Southern Europe and the UK the number of exceedance hours per year is

respectively 364, 260 and 780 according to the simulations. The high exceedance hours for Eastern Europe and UK are caused by the use of a gas oven in a relatively small kitchen. Citizens residing in urban areas and cooking on gas might even be exposed to values exceeding the EU annual ambient Limit Value of 40 µg/m^3.
It should be noted here however that the simulations are based on average cooking behaviour and average building and ventilation conditions and no use of exhaust hoods venting to outside. Eg people cooking much less on their gas stove, or using an effective exhaust hood venting to outside could potentially have exposures below the limit values.

Cooking on gas has a large influence on the indoor NO_2 concentration. Depending on the kitchen size, the ventilation flow and the air tightness, the time averaged NO_2 increase in the simulation study (see Chapter 3) ranges from 13 to 45 µg/m^3 for a deposition rate of 0.75 per hour. This coincides well with the WHO[8] assumption that '*having a gas stove was equivalent to an increased average indoor level of 28 µg/m^3 compared to homes with electric stoves'*.

Use of the oven can lead to very high concentrations, above 1000 µg/m^3. Especially in small kitchens high concentrations can be reached. This effect of higher risk from gas cooking in smaller spaces, even when they are reasonable ventilated, has also been reported in literature[62].
Larger kitchens have a larger volume which lead to more dilution. With the same ventilation one would expect in larger kitchens that it would take longer to dilute the NO_2 contamination. However, the exposure times are comparable for the kitchen sizes between 30 and 100 m^3, typically 3 hours after starting with the cooking. This can be explained with a higher deposition effect in the larger kitchens.

The use of a ducted range hood with 55% efficiency reduces the average concentrations by 54%, 62%, 30% and 49% respectively for Southern, Eastern and Western Europe and the UK. The maximum concentration is even reduced by 71%, 78%, 59% and 81%. With a ducted range hood the exceedance time above 200 µg/m^3 is reduced to zero by using ducted range hoods. The lower reduction values for Western Europe can be explained with the fact that we assumed there a mechanical exhaust system.
The calculated reduction is much higher than what has been measured by Paulin[74], who did not measure an reduction, but instead a non-significant increase after instalment of a range hood. It was unclear if the lack of efficiency was due primarily to lack of use of the hoods. It may also be possible that in some houses the instalment of the hoods increased the ventilation, also when not being used. And that due to the relative high ambient concentration in Baltimore City this had led to additional infiltration of NO_2.

To be able to achieve a more accurate estimate of the number of households that exceed the guideline and legal limits values, Monte Carlo simulations should be made based on sampling distributions of cooking durations, cooking emissions, ventilation and airtightness analogous to what Logue[88] did for Southern California. Unfortunately detailed information about these factors for the EU27 and UK is not currently available.

Furthermore, the deposition rate has a large effect on the simulation results. The simulation with a lower deposition rate of 0.5 per hour increases the average NO_2

concentration with 20 up to 37%. The simulation with a higher deposition rate of 1 per hour reduces the average NO_2 concentration with 13 up to 20%. Deposition data are mainly based on older studies[87] or from laboratory situations (see appendix B). For accurate calculations the deposition should be derived from more recent representative field studies.

4.3 What are the health costs and the DALYs associated with gas cooking?

For the EU27 the population attributable fraction (PAF) of paediatric asthma diagnosed by a doctor due to gas stoves amounts 7.3% (see paragraph 2.3). In the UK, where the number of households cooking on gas is higher than the EU average, 11.5% of paediatric asthma cases be avoided when the risk factor cooking on gas is removed. Asthma is assumed to be a chronic disease, thus most children having asthma due to cooking on gas end up as adults having asthma. Therefore the PAF multiplied with the societal cost due to asthma is a good predictor for the asthma health cost associated with gas cooking appliances.

Based on the 2019 health data[81] the number of DALYS lost due to asthma in the EU27 was estimated at 1 million DALY and for the UK 275.000 DALY. This is an increase compared to the estimate of 697.000 for the EU28 based on WHO 2011 data. Multiplied with the PAF of paediatric asthma this would mean 73,000 and 32,000 DALY in respectively the EU and the UK due to cooking on gas.

Based on 2019 data provided by the International Respiratory Coalition[81] and the PAF of paediatric asthma the societal yearly cost of asthma related to gas cooking appliances are estimated at 3.5 billion euro for the EU27 and 1.6 billion euro for the UK. This estimate is based on the monetized Disability-adjusted life years (DALY) and is calculated as the product of the number of DALY and the Gross Domestic Product (GDP) per capita.

To put these numbers in perspective a comparison is made with an Australian study[16] in which the PAF for childhood asthma associated with gas stoves (12,3%) was higher than the PAF for childhood asthma associated with damp housing (7,9%). Overall 38% of Australian households used piped natural gas for stovetop cooking and 26% of the houses have dampness problems.

4.4 What is the effect of energy transition?

According the simulations in Chapter 3 the effect of retrofitting energy-efficiency to improve the thermal performance of homes seems to be limited on the indoor NO_2 concentration. For Eastern Europe and UK there is an increase in the number of hours that the hourly NO_2 concentration is above 200 $\mu g/m^3$. For Southern Europe, Eastern Europe and the UK the increase in weekly averaged concentration is respectively 25%, 3% and 10%. While for Western Europe a decrease of 4% is predicted. This can be explained by two effects that counteract each other:

1. Due to the higher air tightness there is less infiltration. This leads to less dilution of cooking peaks and thus higher maximum concentrations.
2. On the other side, due to the lower infiltration, less NO_2 from the ambient air enters the houses. This reduces the background concentration.

The limited effect of increased air tightness on the indoor NO_2 concentration in the simulation study is in line with the results of an Irish fieldstudy[93] in which in 15 dwellings the indoor air quality before and after a retrofit have been measured. Although the air leakage has been reduced, there was a non-significant decrease of the NO_2 concentration from 6.8 to 6.0 µg/m^3. At the same time after the retrofit there was a significant increase of CO_2 and $PM_{2.5}$. And in the seven most air tight houses there was also a significant increase in formaldehyde concentration.
A modelling study by Fabian[40] predicted a 15% increase in NO_2 concentration due to weatherisation of houses in Boston. A recent modelling study from 2021[35] indicate that retrofits lead to overall better health outcomes and healthcare cost savings if reduced air exchange due to energy saving air tightening is compensated with mechanical ventilation.

4.5 What are the preferred measures to prevent exposure to these contaminants?

According to the simulation study in Chapter 3 the largest reduction of the NO_2 indoor concentration is reached by switching from cooking on gas to electrical cooking. The exceedance frequency of hourly concentrations above 200 µg/m^3 is reduced to zero for all regions.
The weekly averaged reduction is 84%, 89%, 52% and 66% respectively for Southern, Eastern and Western Europe and the UK. The high reductions for Southern and Eastern Europa can be explained with the assumed low ambient concentrations for rural areas. The 52% – 66% reductions for Western Europe and UK based on a city location (with ambient concentrations of respectively 40 and 50 µg/m^3) coincide well with the reduction of 51% measured by Paulin[74] due stove replacement. This study was executed in Baltimore city with an ambient NO_2 concentration of 55 µg/m^3.
Studies towards the effect of range hood are not conclusive. Despite in some studies no or even a detrimental[74] effect on nitrogen dioxide concentration have been reported, positive health effects have been reported in other studies[39].

Since cooking with electric burners also produces pollutants like $PM_{2.5}$, kitchen exhaust ventilation and preferably combined with effective range hoods should be available in all homes and operated as a precaution whenever cooking occurs[58]. Legislation with regard to ventilation provisions should be initiated to make sufficient capture efficiency possible.

4.6 Which factors should be integrated into a representative field study?

Passive NO_2 measurement

As passive NO_2 sensors are relatively cheap, accurate, small and do not make noise they are the ideal sensors to be placed in kitchen, living room, bedroom and just outside every household to be considered.

Continuous NO_2 measurement

Most field studies up to now rely on passive sampling which renders weekly or two weekly averaged NO_2 concentrations. For health effects also peak concentrations are important. The WHO and EU therefore have setup hourly guidelines and limit values. In order to verify compliance it is important to measure NO_2 also with continuous measurement, e.g. with a one-minute interval.

Fine particulate ($PM_{2.5}$)
The flue gases due to gas burning do not emit measurable amounts of $PM_{2.5}$. However there are indications that cooking on gas involves higher pan temperatures and therefore might generate more $PM_{2.5}$ due to evaporation of cooking oil. Optical $PM_{2.5}$ sensors are relative small and are often combined with a CO_2 relative humidity and temperature sensor. These sensors are important to describe the measurement conditions. Based on the decay rate of CO_2 when no people are present the air exchange rate can be estimated.

Detailed measurement: ultra-fine particles (UFP)
It is advised to measure in a limited number of houses in the Netherlands and the UK ultra-fine particles. To set up the equipment requires specialist personnel. Peak concentrations of UFP from gas and electric stoves occur at a particle size of about 5 nm. A water based CPC might be the most promising choice for measuring ultra-fine particles in a field study due to the absence of harmful volatile organic emissions. However a water-based CPC might have loss of detection efficiency when being used to measure UFP in the presence of oil droplets from stir frying. Therefore the UFP count reported by such a device in a field study might be only representative for meals without (stir) frying. This would involve the need to keep a diary.

Detailed measurement: methane
It is advised to measure in a limited number of houses in the Netherlands and the UK methane leakage due to cooking on gas. As the concentrations are low this requires specialist measurement equipment and personnel. It might even be necessary to temporarily partition the kitchen from the living room with plastic foils.

5 Literature

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6 Signature

Delft, 8 December 2022	TNO
ValidSigned by Ir. ing. M. Steins on 2022-12-08 16:51:13	ValidSigned by Ir. P. Jacobs on 2022-12-08 16:58:50
Ir. ing. M. Steins Research Manager	Ir. P. Jacobs Author

A Simulation results at deposition rates 0.5 and 1 h^{-1}

Table 18 Summary of NO_2 simulation results for the current situation, **deposition 0.5 per hour**.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	30	46	34	83
Maximum [µg/m^3]	436	834	287	1270
Background [µg/m^3]	5	5	17	19
Increase due cooking [µg/m^3]	**25**	**41**	**17**	**54**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*No (5*)*	*No (6*)*	*No (6*)*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*No*
Below EU hourly 200 µg/m^3	*No (5**)*	*No(10**)*	*No (3**)*	*No (16**)*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

Table 19 Summary of NO_2 simulation results for the current situation, deposition 0.75 per hour.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	24	34	27	68
Maximum [µg/m^3]	408	730	268	1192
Background [µg/m^3]	3.9	3.7	13	23
Increase by cooking [µg/m^3]	**20**	**30**	**13**	**45**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*No (5*)*	*No (2*)*	*No (5*)*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*No*
Below EU hourly 200 µg/m^3	*No (5**)*	*No (7**)*	*Yes*	*No (15*)*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

Table 20 Summary of NO_2 simulation results for the current situation, **deposition 1 per hour**.

	Southern Europe	**Eastern Europe**	**Western Europe**	**UK**
Weekly average [µg/m^3]	20	27	22	58
Maximum [µg/m^3]	382	645	251	1123
Background [µg/m^3]	3	3	11	19
Increase due cooking [µg/m^3]	**17**	**24**	**11**	**39**
Below WHO annual 10 µg/m^3	*No*	*No*	*No*	*No*
Below WHO daily 25 µg/m^3	*Yes*	*No (2*)*	*Yes*	*No (7*)*
Below EU annual 40 µg/m^3	*Yes*	*Yes*	*Yes*	*No*
Below EU hourly 200 µg/m^3	*No (5**)*	*No (6**)*	*Yes*	*No (13**)*

** Number of exceedance days per week* ***Number of hours per week exceeding 200 µg/m^3*

B NO$_2$ emission based on O'Leary

In the TNO Indoor Air Quality laboratory in 2017 measurements have been carried out to determine the PM$_{2.5}$ emission during cooking of full meals. These measurements have been reported in Indoor Air[4]. This appendix presents data not previously published that was collected during these experiments. The preparation of the meals is described in full detail in the paper. Table 21 summarizes the meals and lists additional information on the gas consumption per meal. All meals have been cooked 5 times. Figure 12 shows the end result of cooking all meals once.

Table 21 Meal description[4] with cooking time and total gas use.

Nr.	**Description**	**Cooking time [min]**	**Gas use [litres]**
1	Chicken breast filet, fried potatoes, French green beans	28	115
2	Chicken breast filet, cooked potatoes, French green beans	28	110
3	Pasta Bolognese	28	103
4	Stir fried vegetables with chicken breast	17	57

Figure 12 From left to the right meal 1 to meal 4 on two one person plates.

During the measurements the NO/NO$_2$ concentration has been measured with an Envitec NOx monitor, model 200E. The gas flow has been measured with two parallel Bronkhorst F-201EV mass flow controllers. All meals have been cooked five times. The resulting NO$_2$ concentration and the gas flow during the first repetition are shown in Figure 13 till Figure 16.

The NO$_2$ emission per meal Table 22 has been determined with a correction for deposition and ventilation as described by Ott.

Table 22 NO_2 average concentration during cooking and 30 minutes thereafter, emission and deposition rate per meal, 95% confidence interval between brackets.

Nr.	average NO_2 concentration [µg/m^3]	NO_2 emission [mg]	NO_2 emission [ng/J]	deposition rate [1/h]
1	406 [358 – 462]	39,0 [36,2 - 41,9]	9,7 [9 – 10,4]	1.1 [1 – 1,2]
2	450 [410 – 495]	40,9 [39,8 – 42]	10,6 [10,3 – 10,9]	0,9 [0,7 – 1]
3	478 [426 – 537]	47,1 [42 – 52,2]	13,1 [11,7 – 14,5]	0,8 [0,7 – 0,9]
4	214 [184 -248]	16,6 [14,5 – 18,8]	8,3 [7,1 – 8,4]	0,6 [0,5 – 0,8]

There is quite a large variation in the calculated deposition rate. This might be caused by an error in the estimation of the ambient NO_2 concentration. The ambient concentration at the start of each repetition clearly varies and also the ambient concentration at the end seems to be increased. The experiments were in first instance aimed at measuring the $PM_{2.5}$ emission. As the deposition rate of $PM_{2.5}$ is higher, this might have led to accumulation of NO_2 during the repetitions.

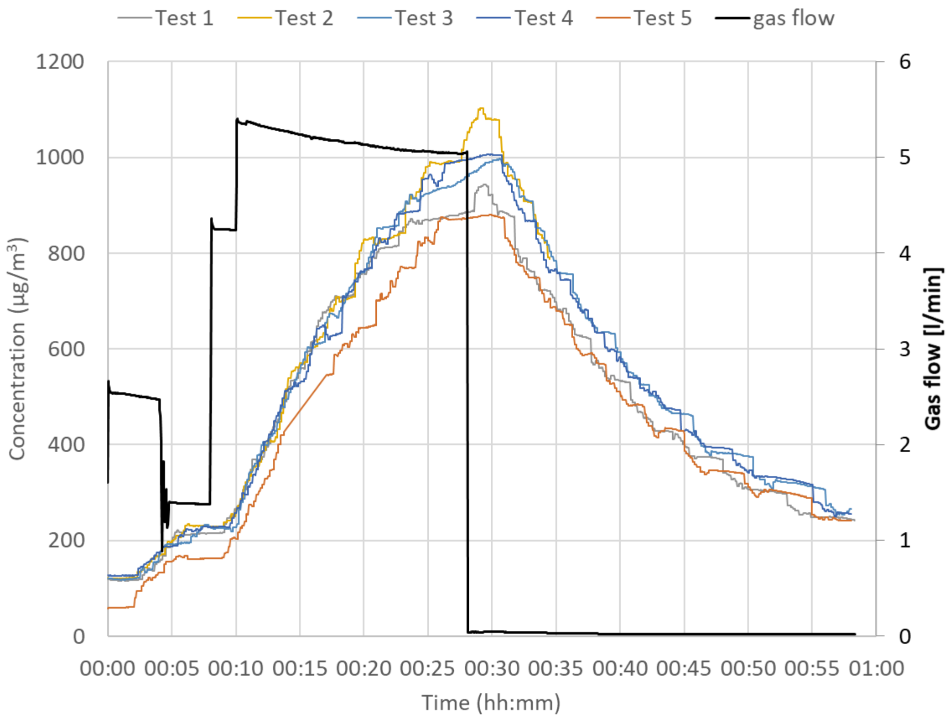

Figure 13 NO_2 concentration during cooking of meal 1 and decay with 75 m^3/h ventilation.

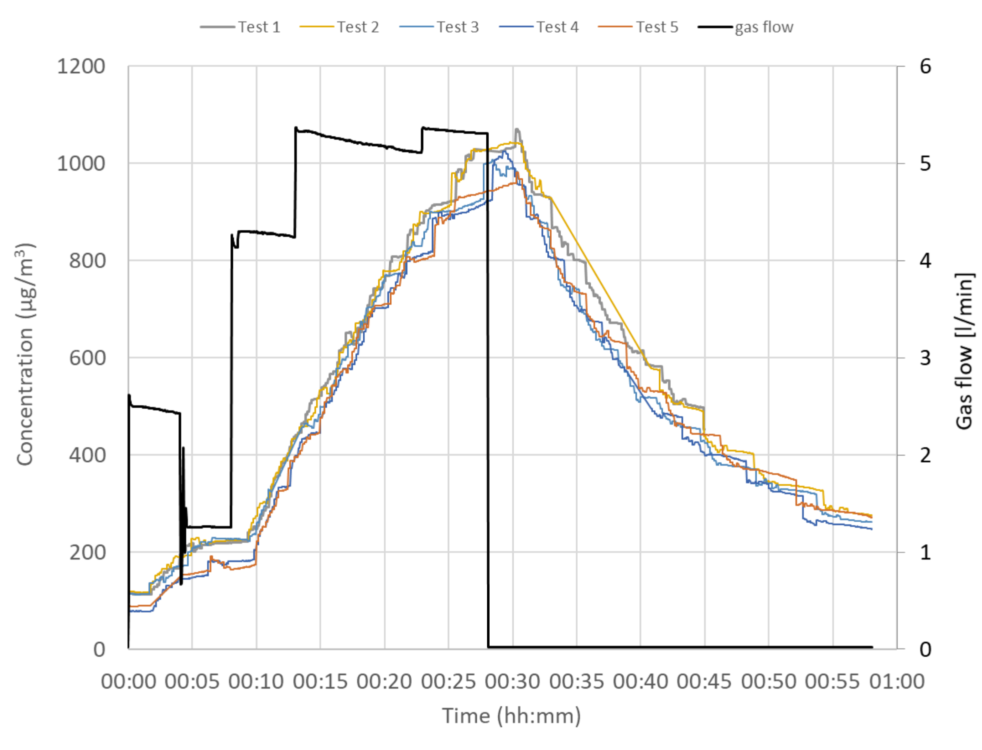

Figure 14 NO_2 concentration during cooking of meal 2 and decay with 75 m^3/h ventilation.

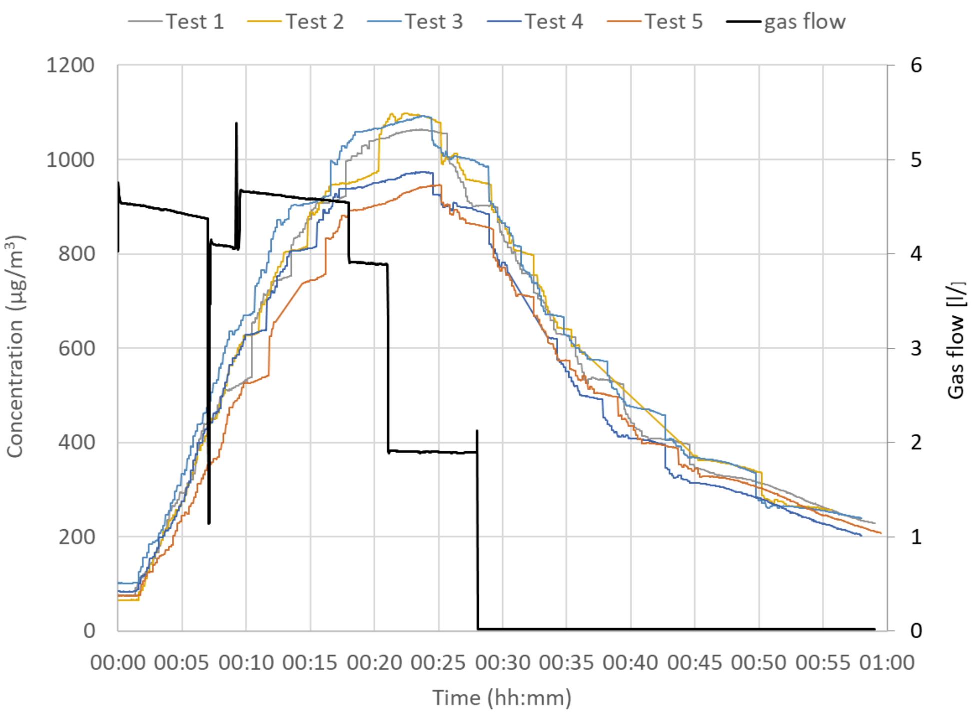

Figure 15 NO_2 concentration during cooking of meal 3 and decay with 75 m^3/h ventilation.

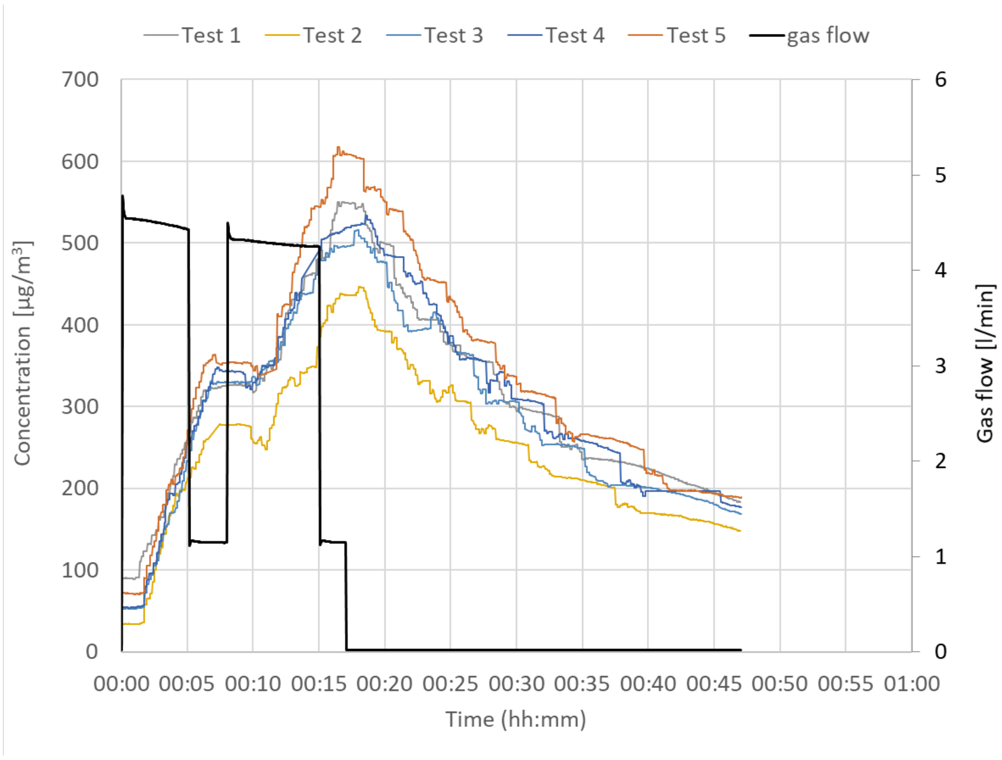

Figure 16 NO_2 concentration during cooking of meal 4 and decay with 75 m^3/h ventilation.